W PRODUCTION AT LEP2 *

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We present some analyses for W physics at LEP2 regarding W mass measurement in fully hadronic and semileptonic channels. We also analyze distributions for measuring possible anomalous gauge couplings. We finally discuss some possible uncertainties and open problems.

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1. Introduction

The relevance of W physics for testing the Standard Model and searching for possible new physics has already been fully analyzed in Ref. [1]. We just remind here that at LEP2 a great part of the efforts will be concentrated in measuring with higher precision the mass of the W and its width, as well as in studying the first direct evidence of phenomena which are characteristic of gauge theories, such as triple gauge couplings and the cancellations among diagrams. From the first issue it will be possible to deduce more accurate and stringent predictions on Higgs mass, if the Higgs particle itself will not be found. From the second, limits or hints for possible new physics can be extracted.

After detailed studies of $e^+e^- \rightarrow W^+W^-$ on shell [2], several codes for four fermion processes [3,4] have been prepared to account for

- off shellness of the W's
- all various possible four fermion final states
- the irreducible background.

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Some of these codes can compute all processes and be fast and precise enough to provide detailed theoretical predictions also on differential cross sections (distributions). Such codes can therefore be used for three purposes:

- to perform fast parton level analyses in order to understand the relevance of cuts, backgrounds, to assess theoretical uncertainties, *etc.*
- to generate unweighted events with hadronization which, after full detector simulation can confront experimental results
- to fit deconvoluted results.

In the following we will give some examples of phenomenological studies for WW physics performed using parton level distributions.

Some of the results have been obtained [5] in common by WTO [6] and WPHACT [7], others by WPHACT alone. These last ones will be indicated by the script WPHACT on the figures. In the common results, the two codes have reached an impressive technical agreement, so that you cannot distinguish in the graphs the curves of the two codes, even if they are obtained with quite different techniques. WPHACT and WTO have some analogy as they both include Coulomb corrections, initial state radiation, naive QCD, they can generate unweighted events and use as preferred renormalization scheme the G_μ one. But they are based on completely different approaches, as the Table I shows:

TABLE I

Some features of the two codes WPHACT and WTO

	WPHACT	WTO
Phase Space	Sequential. 4 momenta explicit	Invariants
Helicity Amplitudes	PHACT [8]	Fermion lines traces [9]
Integration	Vegas [10]	Deterministic Korobov sets
Cuts	θ functions	Exact phase space boundaries
Distributions	Obtained together with σ_{tot}	Evaluated point by point
Options	link to Jetset An. Couplings b masses	Fermion loops

2. Four fermion processes for *WW* physics

In Table II are enumerated the four fermion processes relevant to WW physics. They are divided in three categories: charged current (CC), charged

+ neutral current (MIX) and neutral current (NC). As it is now customary, the numbers following CC, NC or MIX indicate the number of diagrams of that particular channel. Along this line, the three diagrams which correspond to WW production and decay and which are present in all CC and MIX processes are indicated as CC3. The reported neutral current processes are only those with four quarks in the final state. This final state cannot be distinguished from the analogous ones coming from CC and MIX, thus constituting a potentially severe background to WW signal.

TABLE II

Four fermion processes relevant to WW production

CC				
process type		final state		final state
CC9	1	$\mu^- \bar{\nu}_\mu \nu_\tau \tau^+$	2	$\mu^+ \nu_\mu \bar{\nu}_\tau \tau^-$
CC18	1	$e^- \bar{\nu}_e \nu_\mu \mu^+$	3	$e^+ \nu_e \bar{\nu}_\mu \mu^-$
	2	$e^- \bar{\nu}_e \nu_\tau \tau^+$	4	$e^+ \nu_e \bar{\nu}_\tau \tau^-$
CC10	1	$\mu^- \bar{\nu}_\mu u \bar{d}$	5	$\tau^- \bar{\nu}_\tau u \bar{d}$
	2	$\mu^- \bar{\nu}_\mu c \bar{s}$	6	$\tau^- \bar{\nu}_\tau c \bar{s}$
	3	$\mu^+ \nu_\mu \bar{u} d$	7	$\tau^+ \nu_\tau \bar{u} d$
	4	$\mu^+ \nu_\mu \bar{c} s$	8	$\tau^+ \nu_\tau \bar{c} s$
CC20	1	$e^- \bar{\nu}_e u \bar{d}$	3	$e^+ \nu_e \bar{u} d$
	2	$e^- \bar{\nu}_e c \bar{s}$	4	$e^+ \nu_e \bar{c} s$
CC11	1	$s \bar{c} u \bar{d}$	2	$\bar{s} c \bar{u} d$
MIX				
process type		final state		final state
MIX19	1	$\mu^- \mu^+ \nu_\mu \bar{\nu}_\mu$	2	$\tau^- \tau^+ \nu_\tau \bar{\nu}_\tau$
MIX56	1	$e^- e^+ \nu_e \bar{\nu}_e$		
MIX43	1	$d \bar{d} u \bar{u}$	2	$s \bar{s} c \bar{c}$
NC				
process type		final state		final state
NC64	1	$u \bar{u} u \bar{u}$	2	$c \bar{c} c \bar{c}$
NC32	1	$u \bar{u} c \bar{c}$		
NC32	1	$s \bar{s} u \bar{u}$	2	$d \bar{d} c \bar{c}$
NC64	1	$d \bar{d} d \bar{d}$	2	$s \bar{s} s \bar{s}$
NC32	1	$d \bar{d} s \bar{s}$		
NC33	1	$b \bar{b} u \bar{u}$	2	$b \bar{b} c \bar{c}$
NC33	1	$b \bar{b} d \bar{d}$	2	$b \bar{b} s \bar{s}$
NC84	1	$b \bar{b} b \bar{b}$		

The relative importance of the cross sections for semileptonic and fully hadronic processes at LEP2 energies can be deduced from Fig. 1. From it,

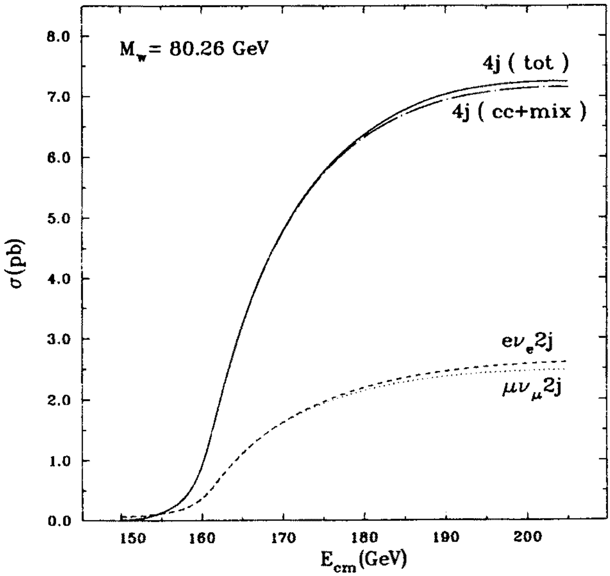

Fig. 1. Total cross section versus $\sqrt{s}$ for the semileptonic and the hadronic channels. The continuous line includes the NC processes reported in Table II with the cuts described in the text.

one can also see that the contribution from NC background to 4 q's cross section can be drastically reduced. The continuous line, which includes this background with all possible gluon exchange diagrams, does not in fact differ much from the chain-dot line. This is due to the request we have made that in each event at least two couples of quarks have both an invariant mass within 10 GeV from M_W.

3. *WW* at threshold

The threshold region (161 GeV) is the ideal place to measure M_W through the dependence of σ_{tot} from M_W itself. Such a dependence is reported in Fig. 2. The errors for such a measure are moreover minimized at threshold. This can be seen from Fig. 3, where we have examined and computed

$$\sigma\left|\frac{dM}{d\sigma}\right|, \qquad \sqrt{\sigma}\left|\frac{dM}{d\sigma}\right|, \qquad \left|\frac{dM}{d\sigma}\right|,$$

which contribute to the statistical and systematic errors on M_W [11]. These sensitivity factors are essentially flat within $(\sqrt{s})_{\min}\pm 1$ GeV and this implies that the minimum error region is stable.

From the run at 161.3 GeV the four LEP Collaborations have already produced preliminary results which, for the LEP average, are at present

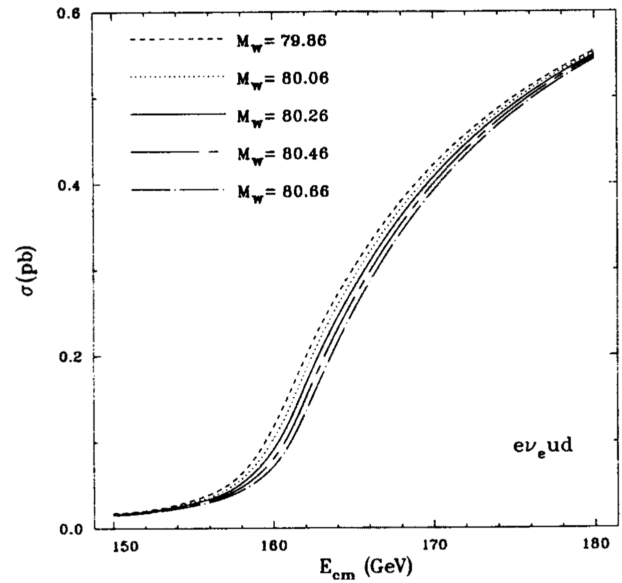

Fig. 2. Total cross section for $e^+e^- \to e^-\bar{\nu}_e u\bar{d}$ at threshold for various W masses

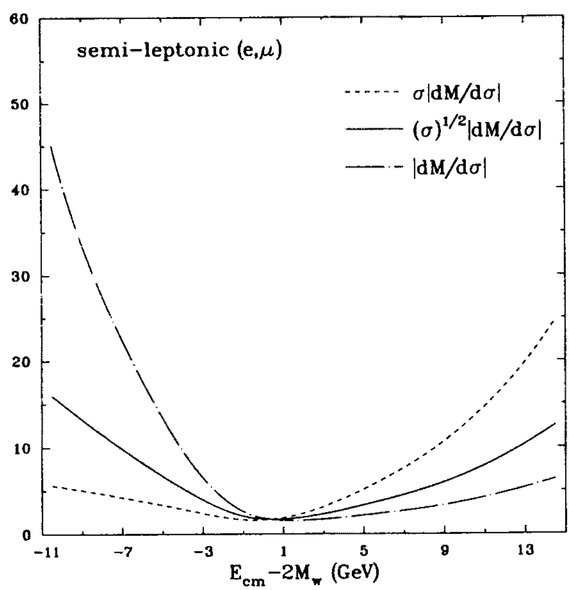

Fig. 3. Statistical and systematic sensitivity factors to the W mass in the semi-leptonic channel as a function of $\sqrt{s} - 2m_W$, for $m_W = 80.26$ GeV.

$\sigma_{WW} = 3.57 \pm .46$ pb, corresponding to $m_W = 80.4 \pm .2 \pm .1$ GeV. σ_{WW} represents the CC3 contribution alone. This implies that from the measured cross sections for the various processes, the theoretical irreducible contribution coming from the other diagrams has been subtracted. The value for m_W has been deduced fitting the resulting CC3 "experimental" value. The irreducible contribution subtracted from the Collaborations has however been computed for only one value of m_W. This is surely not exact, as this contribution contains single resonant diagrams which depend strongly on m_W. We have therefore checked that this approximation is harmless, evaluating the dependence on m_W of the difference between the real processes and CC3. For many processes the difference itself is already very little at this energy. For instance the difference between the cross section for MIX43 and that for CC3 is $\approx .25\%$. Any variation of such a difference is surely irrelevant. The most potentially dangerous process is CC20, as can be seen from Fig. 4. In fact the difference $\sigma(CC20) - \sigma(CC3) \approx -2.5\%$ and the relative difference varies with m_W. The variation of the difference however is only $\approx .2\%$ in the range in the figure.

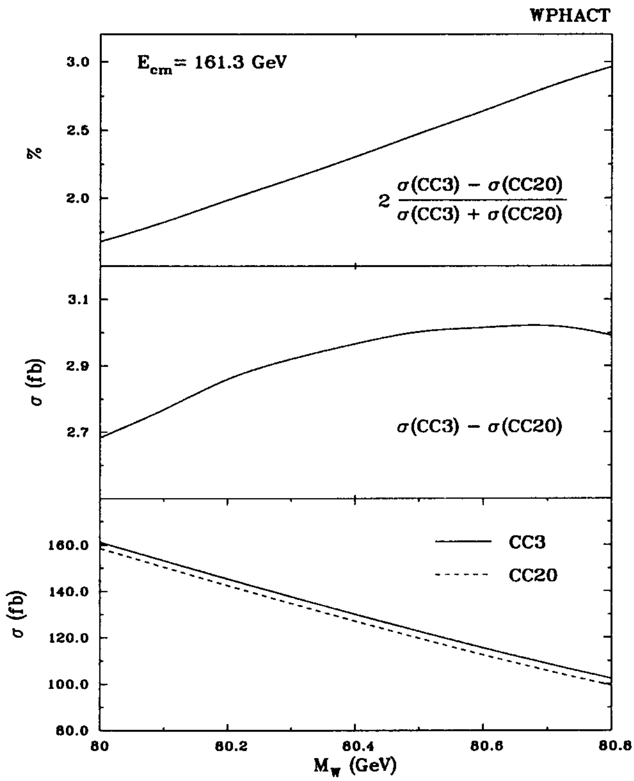

Fig. 4. Variation of $\sigma(e^+e^- \to e^-\bar{\nu}_e u\bar{d}$ and the WW resonant diagrams (CC3) as a function of m_W

4. $e^+e^- \to 4q's$

There are different contributions to four quarks in the final state: CC11 and MIX43 represent the signal for WW processes, while NC64 and NC32 represent the background. All these processes have to be considered with all their possible final states. One has therefore to define a procedure to determine m_W from these channels. In order to reduce the background, we have considered the differential cross sections for the sum of the invariant masses of all couples qq', QQ' for which

$$|m(qq') - m_W| \leq 10\text{GeV}, \qquad |m(QQ') - m_W| \leq 10\text{GeV}.$$

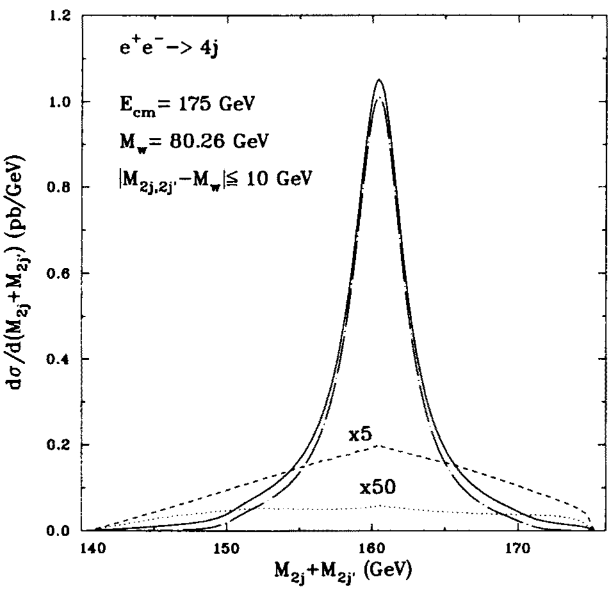

Fig. 5. Distribution of the sum of two invariant masses in the fully hadronic channel at $\sqrt{s}$ =175 GeV. The chaindot curve corresponds to the two invariant masses from $W^{*\pm}$. The dashed one represents the background (magnified by a factor of 5) from two non-resonant invariant masses in CC11 and MIX43 processes, counted with their multiplicity. The dotted curve corresponds to the NC background (magnified by a factor 50). The solid to signal+total background. For each sum, the two invariant masses lie within 10 GeV from m_W

The distribution in invariant masses, summed over all possible four fermion processes is reported in Fig. 5. From it one can deduce that the irreducible background from NC can be easily suppressed, while that coming from all other non CC3 diagrams in CC11 and MIX43 is not negligible. The analogous distribution for $\sqrt{s} = 190$ GeV presents the same features.

5. $e^+e^- \to l\nu qq$

The semileptonic channel is much cleaner than the fully hadronic one. For the latter, even if one can control the NC background, there might still be problems from color reconnection effects and $qqgg$ background.

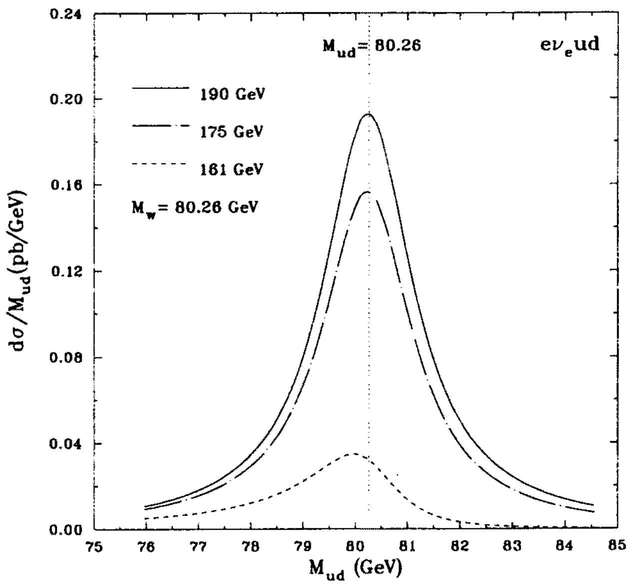

Fig. 6. Invariant mass distribution of $u\bar{d}$ in the $e^-\bar{\nu}_e u\bar{d}$ process, at $\sqrt{s}$ =161 GeV (dashed line), 175 GeV (chaindot line) and 190 GeV (solid line).

The theoretical distributions for the invariant mass formed by the two quarks in CC20 is presented in Fig. 6.

One must notice that, not considering initial state radiation and kinematical effects, the maximum of the distribution for a nominal value $m_W = 80.26$ GeV is expected at $m_W/\sqrt{1+(\Gamma/m_W)^2} = 80.24$ GeV. The maxima computed from the distributions are instead at 78.97, 80.22, 80.24 GeV respectively for $\sqrt{s} = 161, 175, 190$ GeV. This shift has to be taken into account when measuring m_W in this way.

Some results from the runs at 170 and 172 GeV have already been analyzed and in November the Aleph Collaboration has presented [12] a plot for the W mass distribution, based on 8 pb^{-1}. Such distributions in $e^+e^- \to l\nu qq$ are reconstructed experimentally trying to determine both qq and $l\nu$ invariant masses. The total missing 3-momentum is assumed to be that of the neutrino. In such a way one can assign a 4-momentum to all four leptons, and then fits the mass of the W using as constraints the 4 momenta conservations and the request $m(l\nu) = m(qq)$. This last request, is of course not realistic, even if with it one obtains a better fit, as the two invariant

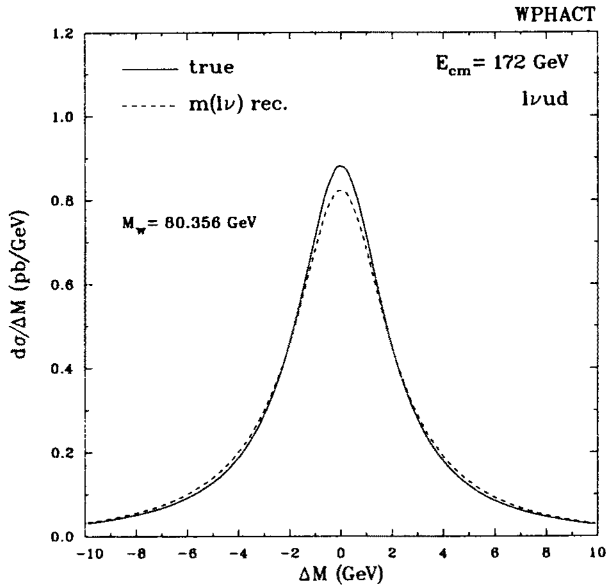

Fig. 7. Distribution for the difference between the invariant masses of lepton neutrino and the two quarks. The dotted line represents the same distribution where the neutrino momentum is reconstructed from missing momentum.

masses at parton level are often not equal. We have studied in Fig. 7 the distribution of the difference between the two invariant masses in two cases: in one (solid line) we use the true neutrino momentum to compute $m(l\nu)$, in the other (dashed) the reconstructed one.

Also the equality $\overline{p}_\nu = \overline{p}_{\rm miss}$ which is used for reconstructing neutrino momentum is in general not true. It would be true only if initial state radiation would not be present. We have therefore studied which possible distortion at parton level such an assumption introduces. The results are presented in Fig. 8, where the solid line corresponds to the true $m(l\nu)$ invariant mass distribution, the dotted line to the one obtained with the reconstructed neutrino momentum and the dashed one to the distribution resulting from taking the mean, event by event, between $m(qq)$ and the reconstructed $m(l\nu)$. This mean distribution somehow mimics the one obtained experimentally with the constraint $m(l\nu) = m(qq)$ in the fit, and one can see that it considerably reduces the distortion.

We have produced this last distribution also for the same binning and luminosity as that produced by Aleph. The result, reported in Fig. 9, is considerably different from that obtained by Aleph MC.

We have therefore introduced a Gaussian smearing in our theoretical distribution, displacing every single reconstructed invariant mass with a

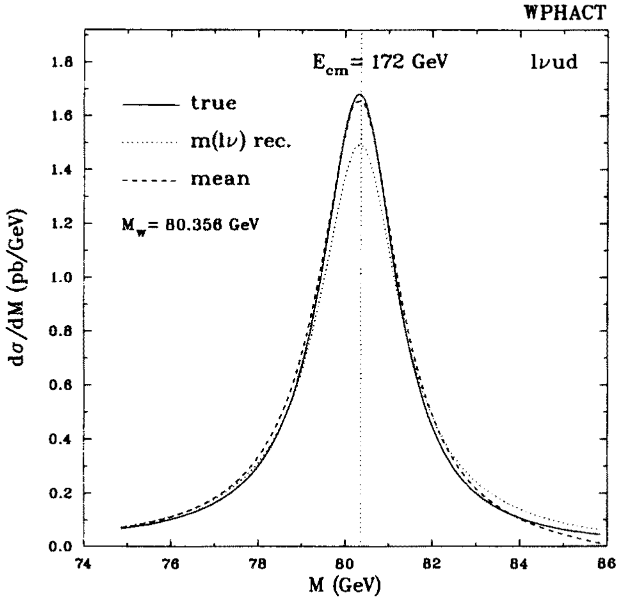

Fig. 8. Distribution for the invariant mass of $l\nu$ for the true (solid line) and reconstructed (dashed) neutrino momentum. The dotted line corresponds to the mean between the latter and the qq invariant mass

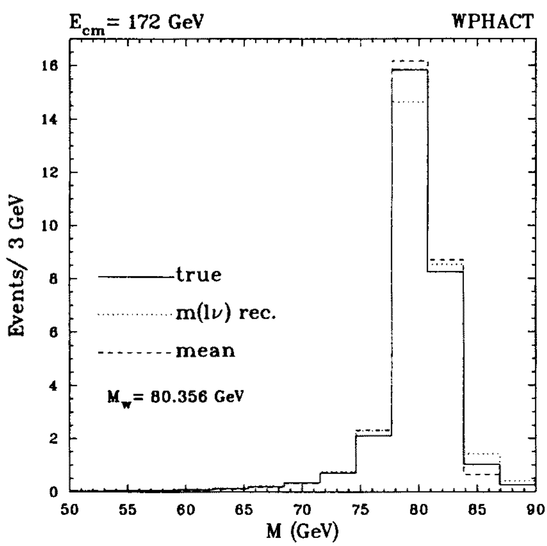

Fig. 9. Same distributions as in Fig. 8 with a 3 GeV binning

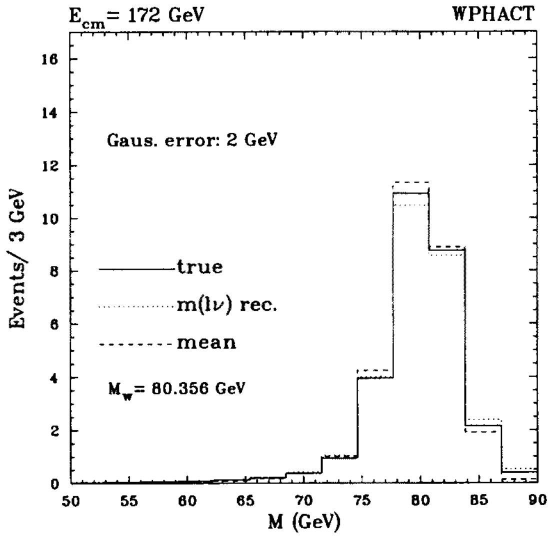

Fig. 10. The distributions for the same variables as in Figs 8, 9 with a 2 GeV Gaussian smearing.

gaussian deviate. The purpose of that is to introduce an error in mass reconstruction. Of course we are aware that the experimental deviation is not simply gaussian and surely it is not the same for all phase space points, nevertheless we observe that with a 2 GeV Gaussian smearing, the distribution of Fig. 10 becomes similar to the Aleph one and we conclude that this is probably the order of magnitude of the experimental error in mass reconstruction.

6. Some considerations on Anomalous Couplings

In this section we just want to explore the following questions:

- May the anomalous couplings influence m_W distributions?
- Which is the best way to eventually discover anomalous coupling effects?

We will not attempt to answer such questions in full generality, but just examine a typical case study with a specific choice of values for the parameters in the so called linear realization:

$$\alpha_W = 0.12\,, \qquad \alpha_{W_\Phi} = 0.1\,, \qquad \alpha_{B_\Phi} = 0.3\,.$$

These parameters correspond to the effective Lagrangian

$$L^{\rm TGC} = ig'\frac{\alpha_{B\Phi}}{M_W^2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) + ig\frac{\alpha_{W\Phi}}{M_W^2}(D_\mu\Phi)^\dagger\vec{\tau}\cdot\vec{W}^{\mu\nu}(D_\nu\Phi) + g\frac{\alpha_W}{6M_W^2}\vec{W}_\nu^\mu\cdot(\vec{W}_\rho^\nu\times\vec{W}_\mu^\rho)\,.$$

Their values are equivalent to the following ones in the parametrization of Ref. [13]

$$\Delta g_1^z = 0.129\,,\quad \Delta k_\gamma = 0.4\,,\quad \Delta k_z = 0.014\,,\quad \lambda_\gamma = 0.12\,,\quad \lambda_z = 0.12\,,$$

and have been chosen as they correspond to an upper bound on new physics scale of about 1 TeV.

The result of our analysis indicate that practically no difference can be seen, at least for this choice of the parameters, in the m_W mass distribution. On the other hand, one can find some differences between the $cos\theta_W$ distributions for the SM and the triple anomalous gauge coupling case, as it results from Fig. 11. It has in fact already been evidenced in the literature [14] that the W angular distribution can be affected by AC. It has however to be noticed that the W angle has to be reconstructed, determining the W momentum from leptons and neutrinos or from two quarks. This surely introduces errors in its determination, so that tiny effects can be missed. For

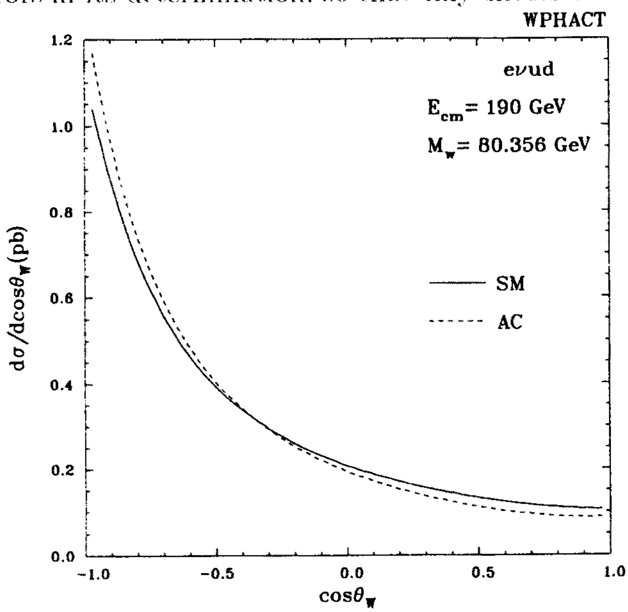

Fig. 11. Differential $\cos\theta_W$ cross section for Standard Model and Anomalous Couplings with parameters described in the text.

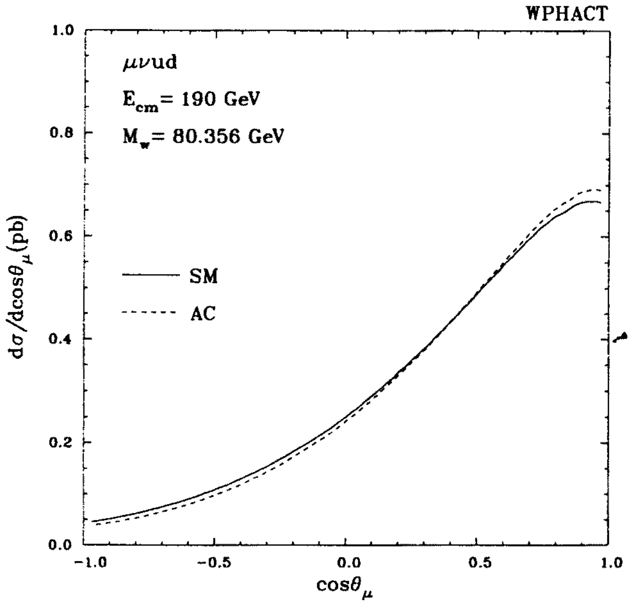

Fig. 12. Differential $\cos\theta_\mu$ cross section for Standard Model and Anomalous Couplings with parameters described in the text.

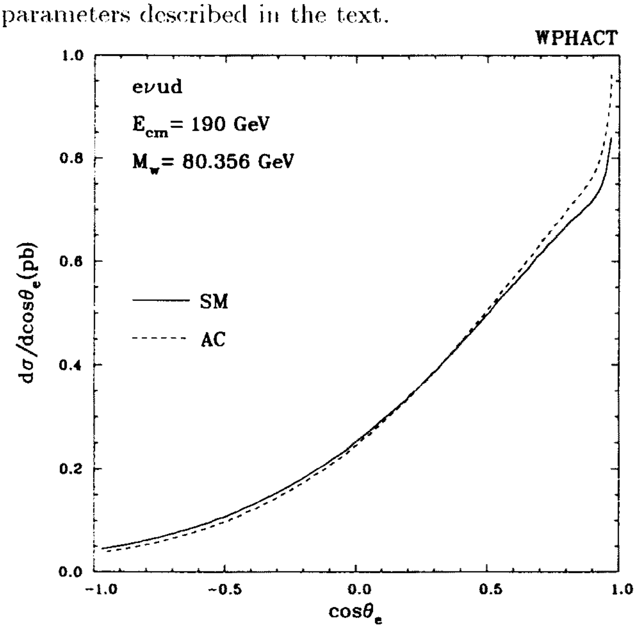

Fig. 13. Differential $\cos\theta_e$ cross section for Standard Model and Anomalous Couplings with parameters described in the text.

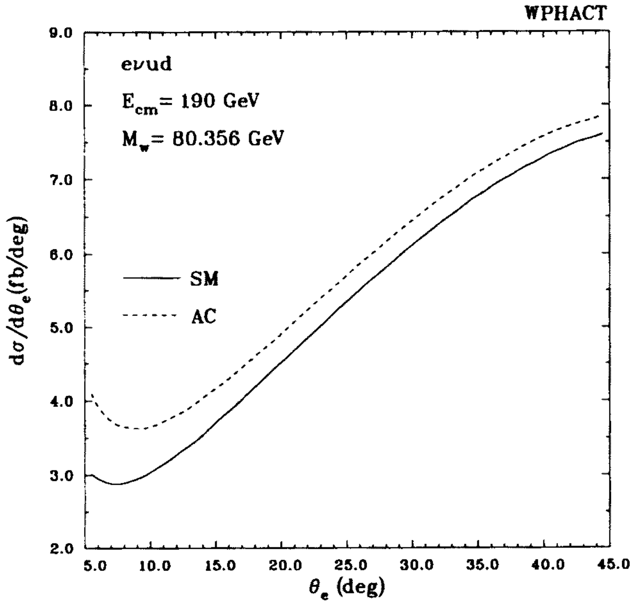

Fig. 14. Differential θ_e cross section for Standard Model and Anomalous Couplings with parameters described in the text.

such reason we have investigated another possibility, which in our opinion seems more promising: that of searching anomalous effects on the lepton distributions. These are surely more easily determined experimentally and the theoretical distributions calculated and reported in Figs 12, 13, 14 show that the effect is surely not less important than in θ_W.

7. Conclusions

There are still some open theoretical problems in WW physics, as for instance how to handle color reconnection or how to interface exact or "naive" QCD corrections with hadronization and parton shower programs. Recently the important theoretical problem of the non-gauge invariance of tree-level calculations in presence of unstable bosons has been solved with the so called fermion loop approach [15]. Also exact QCD calculations have been produced for CC3 and CC10 [16], which confirm the viability in most cases of the so called "naive" corrections. At present, four fermion codes have reached an high reliability and can be used for phenomenological investigations as well as event generators.

We have presented some analyses in which theoretical (parton level) distributions computed to high accuracy have been used to understand different issues of WW LEP2 physics. In particular we have concluded that

- the subtraction of the background at only one value of the mass at threshold is a reasonable approximation
- the background to WW 4 q's signal from the five NC processes is negligible, provided suitable cuts are implemented
- the irreducible background to the same signal from the non CC3 diagrams of CC and MIX processes has to be accounted for.
- the reconstruction of neutrino momentum from missing momentum in $l\nu qq$ introduces little deviations in m_W distributions
- the experimental mass reconstruction seems to introduce and error of ≈ 2 GeV which broadens m_W distribution
- the anomalous gauge couplings do not affect m_W distributions.
- the best place to search for anomalous couplings effects is probably the lepton angular distributions.

These results are an example, in our opinion, of the complementarity of MC analyses performed generating unweighted events, and using hadronization and full detector simulation, with faster theoretical parton level analysis with high statistical precision. In the former one reproduces exactly the experimental conditions, while in the second case cuts can only be introduced at parton level, but the two together allow to better understand the origin of the different effects.

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