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Standard Model Physics Results from LEP2

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At LEP2 many Standard Model predictions are tested up to centre-of-mass energies of 209 GeV . Fermion pair production cross sections and asymmetries agree well with the theoretical expectation over the entire energy range. The measurements are used to determine the γ/Z interference and to search for contact interactions up to 20 TeV. The cross sections for single-W, ZZ and W^+W^- production agree well with the expectations. The branching fractions of the W boson into hadrons and leptons are determined as well as the CKM matrix element $|V_{cs}|$. Precise measurements of the W mass and width are presented yielding $M_W = 80.427 \pm 0.046$ GeV and $\Gamma_W = 2.12 \pm 0.11$ GeV . All electroweak data are very consistent with the Standard Model predictions. In a combined fit using the recent value of $\Delta\alpha^{(5)}_{\rm had}(s)$ the mass of the Higgs boson is constrained to $M_H = 88^{+60}_{-37}$ GeV .

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1 Introduction

The LEP accelerator has provided since its start in 1989 many possibilities to check Standard Model [1,2] (SM) predictions. During the first years the accelerator was operated at the Z-pole (LEP1) and the four LEP experiments, ALEPH, DELPHI, L3 and OPAL collected some 15 million hadronic and 2 million leptonic Z decays. These data allowed a precise determination of the properties of the Z boson [3]. In the second phase of LEP, LEP2, the centre-of-mass energy, $\sqrt{s}$, was successively increased up to $\sqrt{s} = 209$ GeV allowing the production of $\mathrm{W^+W^-}$ and ZZ pairs. More than 8000 W-pair events have been collected per experiment and are used to determine in particular the mass and width of the W boson [4]. Combining the LEP results with other electroweak precision measurements allows thorough consistency tests of the SM and to constrain the mass of the Higgs boson [5,6].

To match the statistical accuracy of the large data samples collected at LEP – especially at energies above the Z-pole – the corresponding theory programs have been improved. For 2-fermion processes the programs ZFITTER [7], TOPAZ0 [8] and KKMC [9] have now a precision better than 0.2% for the total hadronic and leptonic[1] cross sections at high energies. The KKMC program covers the entire energy range from τ– and b–factories over LEP to linear colliders. Also for 4-fermion processes adequate precision has been reached. Using the double-pole approximation [10] RacoonWW [11] and YFSWW3 [12] calculate the $\mathrm{W^+W^-}$ cross section within 0.4% above the production threshold. The cross section for the process $\mathrm{e^+e^-} \to We\nu$ is calculated within 4-5% accuracy by WPHACT [13], grc4f [14] and WTO [15] using the fermion loop scheme [16]. The programs YFSZZ [17] and ZZTO [18] predict the Z-pair production cross section within 2%. Details can be found in the proceedings of the LEP2MC workshop [19,20]. Generally there is now an excellent match in precision between theoretical predictions and experimental measurements.

2 Fermion Pair Production

At centre-of-mass energies well above the Z-pole photon radiation becomes important. The effects to consider are initial and final state photon radiation, interference between these and the production of additional fermion pairs by a photon or Z boson. The main interest is in events where the annihilation took place at a high effective centre-of-mass energy, $\sqrt{s'}$, which is defined as the mass of the outgoing lepton pair or of the γ^*/Z propagator. Results are given by all four experiments for events with $\sqrt{s'} > 0.85 \cdot \sqrt{s}$. The results for the reactions $\mathrm{e^+e^-} \to \mathrm{hadrons}(\gamma)$, $\mathrm{e^+e^-} \to \mu^+\mu^-(\gamma)$ and $\mathrm{e^+e^-} \to \tau^+\tau^-(\gamma)$ are combined taking properly into account the statistical and systematical uncertainties and their correlations [21].

[1] For Bhabha scattering the precision is estimated to 2% for an angular range of $30^\circ < \vartheta < 150^\circ$.

The combined results for the total cross sections are in Figure 1 compared to the SM predictions for all three processes. The measurements agree well with the theoretical expectations. For muon and tau pair production also the differential cross sections, $d\sigma/d\cos(\vartheta)$, have been determined. The result for muon pair production is also shown in Figure 1 for centre-of-mass energies from 183 GeV to 202 GeV. Also the forward-backward asymmetries for these processes are in good agreement with the SM. For hadronic final states the ratios of cross sections for b quarks and c quarks to the total hadronic cross section, R_b and R_c, as well as the forward-backward asymmetries for these flavours are determined. Within the limited statistics of the measurements good agreement with the SM is observed.

The reaction $e^+e^- \to f\bar{f}$ has contributions from photon exchange, from Z boson exchange and from γ/Z interference. Within the S-Matrix approach [22] the lowest–order total cross sections and forward–backward asymmetries are parametrised in the following way:

$$\sigma^0_a(s) = \frac{4}{3}\pi\alpha^2\left[\frac{g^a_f}{s} + \frac{j^a_f(s-\overline{m}^2_Z) + r^a_f\, s}{(s-\overline{m}^2_Z)^2 + \overline{m}^2_Z\overline{\Gamma}^2_Z}\right], \text{for } a = \text{tot}, \text{fb},$$

$$A^0_{fb}(s) = \frac{3}{4}\frac{\sigma^0_{fb}(s)}{\sigma^0_{tot}(s)}, \qquad \text{with} \qquad \sigma^0_{fb} = \frac{4}{3}(\sigma_f - \sigma_b).$$

The S–Matrix ansatz defines the Z resonance using a Breit–Wigner denominator with an s–independent width. In other approaches, a Breit–Wigner denominator with an s–dependent width is used, which implies the following transformation of the values of the Z boson mass and width: $M_Z = \overline{m}_Z + 34.1$ MeV and $\Gamma_Z = \overline{\Gamma}_Z + 0.9$ MeV. In the following, the fit results are quoted after applying these transformations. The S–Matrix parameters r_f, j_f and g_f give the Z exchange, γ/Z interference and photon exchange contributions for fermions of type f, respectively. For hadronic final states the parameters r^{tot}_{had}, j^{tot}_{had} and g^{tot}_{had} are sums over all produced quark flavours.

While in the standard fits to determine the Z boson mass the γ/Z interference is fixed to its SM expectation, in S-matrix fits it is left free leading to an additional uncertainty on M_Z. Figure 2 shows the 68% confidence level contours in the (M_Z, j^{tot}_{had}) plane for the L3 data taken at the Z–pole and after including the 130–189 GeV measurements [23]. The improvement resulting from the inclusion of the high energy measurements is clearly visible. The S-matrix fit agrees well with the results from the standard fit indicated by the vertical band. Figure 2 also shows the potential [2] result when combining all LEP data [21] and the Tristan [24] results. The total error on M_Z is expected to be 2.3 MeV showing that it is possible to remove the additional uncertainty from the γ/Z interference on M_Z almost completely.

The measured fermion pair cross sections and asymmetries can also be used to set limits on contact interactions, fermion sizes, extra space dimensions, TeV strings, gravitons and other new physics effects. For example, contact interactions setting

[2] Only some preliminary LEP1 results within the S-Matrix framework are available and systematic errors are not fully taken into account.

Table 1: Preliminary limits on contact interactions from LEP combined data collected at centre-of-mass energies from 130 GeV to 202 GeV.

	Helicity configuration				Energy scale [TeV]	
	η_{RR}	η_{LL}	η_{LR}	η_{RL}	Λ_-	Λ_+
AA	± 1	± 1	∓ 1	∓ 1	13.9	17.6
VV	± 1	± 1	± 1	± 1	17.2	20.4
RR	± 1	0	0	0	9.7	12.3
LL	0	± 1	0	0	10.2	12.8

in at an energy scale Λ can be described by the following Lagrangian [25] where by convention the couplings g are normalised by $g^2/4\pi = 1$ and the helicity amplitudes obey $|\eta_{ij}| = 0, 1$:

$$\mathcal{L} = \frac{1}{1+\delta_{ef}} \sum_{i,j=\mathrm{L,R}} \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} (\overline{\mathrm{e}}_i \gamma^\mu \mathrm{e}_i)(\overline{f}_j \gamma_\mu f_j),$$

δ_{ef} is the Kronecker symbol being one for Bhabha scattering and zero otherwise. A contact interaction, even at very high energy scales, can be detected at LEP2 by its interference effects with the SM by modifications to the differential cross sections.

$$\frac{d\sigma}{d\cos\theta} = \frac{d\sigma^{\mathrm{SM}}}{d\cos\theta} + c_{\mathrm{int}}(s, \cos\theta)\frac{1}{\Lambda^2} + c_{\mathrm{ci}}(s, \cos\theta)\frac{1}{\Lambda^4}.$$

Such fits are done to the LEP combined measurements [21] and the resulting limits on the energy scale are in the range from 10 TeV to 20 TeV depending on the helicity configuration. The results are summarised in Table 1.

3 Boson Production Cross Sections

The high centre-of-mass energies obtained at LEP2 allow the production not only of fermion pairs but also of boson pairs, $\mathrm{W^+W^-}$and ZZ, and the production of single W bosons.

The production of Z boson pairs tests the SM in the neutral-current sector and is sensitive to scenarios for new physics like extra space dimensions or couplings between neutral gauge bosons. All experiments have measured the ZZ cross section at $\sqrt{s}$ up to 208 GeV. The results are combined using the expected statistical error and systematic uncertainties [26]. They are compared to predictions from YFSZZ and ZZTO in Figure 3 and show no significant deviation from these theoretical models.

No new measurement for single W production ($e^+e^- \rightarrow We\nu$) has been provided above $\sqrt{s} = 202$ GeV but the fermion loop scheme [16] has been introduced as an additional theoretical model. The data are compared with the updated, slightly lower theoretical predictions in Figure 3 showing good agreement.

4 W^+W^- Production

At centre-of-mass energies above 160 GeV the production of W^+W^- pairs is possible. Both W bosons decay into two fermions each producing three different types of final states. About 45.6% of the events decay fully hadronically. These are balanced events of high multiplicity. In $3 \times 14.6\%$ one W decays hadronically while the other one decays leptonically resulting in 2 jets and a high energetic lepton. A τ lepton can decay into a third, narrow jet instead of an electron or muon. Fully leptonic decays are characterised by low multiplicity and a lot of missing energy. The leptons are typically acoplanar.

Events of all three topologies are selected by the four LEP experiments to measure the total production cross section of W^+W^-pairs. The combined LEP cross section [26] is shown in Figure 4 and compared to the predictions of the programs Gentle 2.1 [27] (at centre-of-mass energies below 170 GeV) and RacoonWW and YFSWW 1.14 above threshold. Over the full energy range an excellent agreement between the measurements and the SM is found.

Table 2: Preliminary hadronic and leptonic branching fractions of the W boson measured by the four LEP experiments and the combined results. All numbers are given in percent.

	W→hadrons	W→ $e\nu$	W→ $\mu\nu$	W→ $\tau\nu$
ALEPH	67.22 ± 0.53	11.19 ± 0.34	11.05 ± 0.32	10.53 ± 0.42
DELPHI	67.81 ± 0.61	10.33 ± 0.45	10.68 ± 0.34	11.28 ± 0.56
L3	68.47 ± 0.59	10.22 ± 0.36	9.87 ± 0.38	11.64 ± 0.51
OPAL	67.86 ± 0.62	10.52 ± 0.37	10.56 ± 0.35	10.69 ± 0.49
LEP	67.78 ± 0.32	10.62 ± 0.20	10.60 ± 0.18	11.07 ± 0.25

From the selected events also the decay fractions of the W boson into hadrons and the three lepton flavours are determined. DELPHI and L3 used data from centre-of-mass energies of 161 GeV to 202 GeV while ALEPH and OPAL analysed data up to 207 GeV. The results are listed in Table 2. The branching fractions for the three lepton flavours agree with each other and support the hypothesis of lepton universality. The LEP combined leptonic branching fraction of the W boson is

$Br(\mathrm{W} \to \mathrm{l}\nu) = 10.74 \pm 0.10$ %. This direct measurement can be compared to the indirect extraction at the TEVATRON where the combined results from CDF and D0 [28] yield $Br(\mathrm{W} \to \mathrm{l}\nu) = 10.43 \pm 0.25$ %.

From the hadronic branching fraction it is possible to determine the element $|V_{cs}|$ of the Cabbibo-Kobayashi-Maskawa mixing matrix exploiting the formula:

$$\frac{Br(\mathrm{W} \to \mathrm{hadrons})}{1 - Br(\mathrm{W} \to \mathrm{hadrons})} = \sum \left|V_{ij}^2\right| \left(1 + \frac{\alpha_s}{\pi}\right).$$

With LEP data a value of $|V_{cs}| = 0.989 \pm 0.016$ is obtained. This value is in good agreement with the more direct determination using events with tagged charm of $|V_{cs}| = 0.95 \pm 0.08$ [26].

5 W Mass Measurement

The mass of the W boson is determined at LEP in two different ways. Close to the production threshold the total cross section depends strongly on $\mathrm{M_W}$. For $\sqrt{s}$= 161 - 172 GeV the mass is determined from σ_{WW} to be $\mathrm{M_W} = 80.40 \pm 0.22$ GeV [4]. At higher centre-of-mass energies where the dependence of $\mathrm{M_W}$ on σ_{WW} is reduced the mass is reconstructed directly from the W decay products.

Table 3: The values obtained for the mass and the width of the W boson obtained by the four LEP experiments and their combination from data taken at $\sqrt{s}$= 172 - 202 GeV. All numbers are preliminary.

	$\mathrm{M_W}$ [GeV]	Γ_{W} [GeV]
ALEPH	80.440 ± 0.064	2.17 ± 0.20
DELPHI	80.380 ± 0.071	2.09 ± 0.15
L3	80.375 ± 0.077	2.19 ± 0.21
OPAL	80.485 ± 0.065	2.04 ± 0.18
LEP	80.427 ± 0.046	2.12 ± 0.11

From the three possible final states, qqqq, qqlν and lνlν, the fully leptonic is not used because the two undetectable neutrinos inhibit the complete determination of the event kinematics. For the other events leptons and jets are reconstructed and $\mathrm{M_W}$ is determined in a kinematic fit to the measured fermion energies and angles. Constraints from energy and momentum conservation – one for semileptonic and four for hadronic decays – are imposed to improve the resolution. In some analyses the two reconstructed W masses are required to be equal as an additional constraint. For

hadronic decays choosing the correct jet pairing poses an additional problem. The pairing giving the best χ^2 in the fit is choosen. Possible gluon radiation is taken into account by splitting the hadronic events into a 4- and 5-jet sample improving the mass resolution (DELPHI, OPAL).

Table 4: Breakdown of the systematic and statistical errors on M_W for the different decay topologies in the LEP combined measurement.

Source	Systematic Errors on M_W in MeV		
	$qq\ell\nu$	qqqq	Combined
Colour Reconnection	–	50	13
Bose-Einstein Correlations	–	25	7
LEP Beam Energy	17	17	17
ISR / FSR	8	10	8
Hadronisation	26	23	24
Detector Systematics	11	8	10
Other	5	5	4
Total Systematic	35	64	36
Statistical	38	34	30
Total	51	73	47

The invariant mass distributions obtained from data taken at $\sqrt{s} = 192-202$ GeV are shown in Figure 5. The W boson mass is extracted from these spectra by comparing reweighted Monte-Carlo event samples corresponding to different mass hypotheses to data (ALEPH, L3, OPAL). Alternativly, the differential cross sections are convoluted with resolution functions (DELPHI, OPAL) or the mass is determined from a Breit-Wigner fit to the measured mass spectrum (OPAL).

The results for M_W are listed in Table 3. The LEP value is a combination of individual measurements performed at 172 - 202 GeV from the experiments for different channels and years taking errors and correlations into account. The resulting χ^2/dof is 27.1/29. The statistical contribution to the error is 30 MeV, that from systematic uncertainties amounts to 36 MeV.

Currently, the systematic uncertainties dominate the total error on M_W. A part common to all measurements comes from the LEP beam energy determination and amounts to 17 MeV at highest energies [29]. A new beam energy spectrometer that has been installed in 1999 is expected to reduce this error to 7 - 12 MeV [30]. Other systematic uncertainties relevant for all decay channels are hadronisation effects, detector related systematics and effects of initial state and final state radiation.

The fully hadronic decays suffer from specific uncertainties due to hadronic final state interactions (FSI). They occur because the distance between the two decaying W bosons of about 0.1 fm is much smaller than the typical hadronic interactions length of 1 fm. This can give rise to colour reconnection effects [31] or Bose-Einstein correlations [32]. Both can affect the reconstruction of the invariant masses by momentum transfers between particles that stem from different W bosons. Combining the results from the four experiments common uncertainties of 50 MeV for colour reconnection and 25 MeV for Bose-Einstein effects are estimated by comparing different Monte-Carlo models. FSI effects may also show up in the difference between M_W values measured from semi-leptonic or from fully hadronic events. The difference, determined removing systematic errors due to possible FSI effects, amounts to

$$\Delta M_W = M_W(qqqq) - M_W(qql\nu) = +5 \pm 50 \text{ MeV}$$

and is compatible with zero. Recently, possible effects of FSI are also studied in other observable than the W mass which are sensitive to FSI [33], e.g. the particle flow in the overlap region between two jets and particle correlation functions. In future it may be possible to exclude some of the FSI models in a combined LEP analysis, which should reduce the systematic uncertainty on M_W.

Table 4 shows a breakdown of all systematic errors for semileptonic and hadronic final states. Due to the uncertainties related to FSI effects the contribution of hadronic final states to the combined M_W measurement is only 27% while the weight of the semileptonic events is 73%.

The W boson mass $M_W = 80.427 \pm 0.046$ GeV measured at LEP is in striking agreement with its determination at $p\overline{p}$ colliders [34] of $M_W = 80.452 \pm 0.062$ GeV . The resulting average from direct measurements is

$$M_W = 80.436 \pm 0.037 \text{ GeV} .$$

The method of direct reconstruction is also adequate to measure the width of the W boson, Γ_W. The results of the four LEP experiments are shown in Table 3. The combination of the individual measurements is done in the same way as for the determination of M_W. The resulting LEP value is $\Gamma_W = 2.12 \pm 0.11$ GeV and is in agreement with the direct determination by CDF [35] of $\Gamma_W = 2.06 \pm 0.13$ GeV .

6 Standard Model Fits

Many SM parameters are measured at LEP1 and SLD like the mass and width of the Z boson, M_Z and Γ_Z, the hadronic pole cross section, σ^0_{had}, the ratios of leptonic to hadronic widths, R_l, the asymmetry parameters for leptons and b and $c-$ quarks, A^0_{FB}, the τ polarisation and quark charge asymmetry, Q_{FB}. At SLD the measurement of

left-right forward-backward asymmetry and recently the asymmetry for s quarks [36] are done. Finally, the result for the on-shell value of $\sin^2\vartheta_{\mathrm{W}} = 0.2255 \pm 0.0021$ measured by NuTEV/CCFR in ν-nucleon scattering [37] and the value of $\alpha(\mathrm{M_Z^2})$ are added. The latter can be expressed as

$$\alpha(\mathrm{s}) = \frac{\alpha(0)}{1 - \Delta\alpha_{\mathrm{lep}}(\mathrm{s}) - \Delta\alpha^{(5)}_{\mathrm{had}}(\mathrm{s}) - \Delta\alpha^{\mathrm{top}}_{\mathrm{had}}(\mathrm{s})}$$

where all terms except the contribution from the five light quark flavours, $\Delta\alpha^{(5)}_{\mathrm{had}}(\mathrm{s})$, are know with high accuracy. Here a value $\Delta\alpha^{(5)}_{\mathrm{had}}(\mathrm{s}) = 0.02804 \pm 0.00065$ [38] is used. A fit within the Standard Model is performed to these inputs to determine the parameters $\mathrm{M_Z}, m_{\mathrm{t}}, \mathrm{M_H}, \alpha_{\mathrm{s}}$ and $\Delta\alpha^{(5)}_{\mathrm{had}}(\mathrm{s})$.

In Figure 6 the result of the fit is shown in the $\mathrm{M_W}$-m_{t} plane and compared to the direct measurements of $\mathrm{M_W}$ at LEP and $\mathrm{p\overline{p}}$ colliders and of m_{t} at the TEVATRON [39]. The measurements are nicely consistent with the indirect determination from the SM fit. A similar fit using all data except the direct measurement of the top quark mass result in $m_{\mathrm{t}} = 179^{+13}_{-10}$ GeV and when using all data except direct $\mathrm{M_W}$ determinations $\mathrm{M_W} = 30.386 \pm 0.025$ GeV is obtained. Again, these results are in good agreement with the respective direct measurements. This demonstrates the compatibility and the internal consistency of the SM within the existing precision and confirms the SM parameter relations at 1-loop level.

The SM fits can also be used to estimate the mass of the Higgs boson. To do this a series of fits with fixed values of $\mathrm{M_H}$ is performed and the difference in the χ^2 values as shown in Figure 6 is considered. Since the leading radiative correction terms depend on $\log(\mathrm{M_H})$ the constraints that can be obtained are not very stringent. The result using $\Delta\alpha^{(5)}_{\mathrm{had}}(\mathrm{s}) = 0.02804 \pm 0.00065$ is

$$\mathrm{M_H} = 60^{+52}_{-29}\ \mathrm{GeV}\,; \quad \log(\mathrm{M_H}/\ \mathrm{GeV}\,) = 1.78^{+0.27}_{-0.28}.$$

The slight decrease with respect to the previous result [40] is mainly caused by the change in $\mathrm{M_W}$. The central value depends strongly on the top quark mass and the value of $\Delta\alpha^{(5)}_{\mathrm{had}}(\mathrm{s})$ used.

The value of $\Delta\alpha^{(5)}_{\mathrm{had}}(\mathrm{s})$ is obtained by integrating the R_{had} distribution measured in $\mathrm{e^+e^-}$annihilation or calculated in perturbative QCD:

$$\Delta\alpha^{(5)}_{\mathrm{had}}(\mathrm{s}) \propto \int\limits_{4\mathrm{M}_\pi^2}^{\infty} \frac{\mathrm{R(s')\,ds'}}{\mathrm{s'(s'-s)}}$$

Recent results obtained at BES [41] have been used to extract the more precise value $\Delta\alpha^{(5)}_{\mathrm{had}}(\mathrm{s}) = 0.02755 \pm 0.00046$ [6] yielding a higher value for $\mathrm{M_H}$:

$$\mathrm{M_H} = 88^{+60}_{-37}\ \mathrm{GeV}\,; \quad \log(\mathrm{M_H}/\ \mathrm{GeV}\,) = 1.94^{+0.22}_{-0.24}$$

Relying on perturbative QCD the error on $\Delta\alpha^{(5)}_{\rm had}(s)$ is further reduced. With the value $\Delta\alpha^{(5)}_{\rm had}(s) = 0.02738 \pm 0.00020$ [42] one obtains $M_H = 104^{+59}_{-39}$ GeV .

Depending on the value of $\Delta\alpha^{(5)}_{\rm had}(s)$ used in the fit upper limits on the Higgs boson mass of 162 – 215 GeV are obtained at 95% confidence level. The fits suggest that the Standard Model Higgs is light. They are compatible with the results from direct searches for the Higgs that exclude values of M_H below 113.5 GeV at 95% C.L. and strongly indicate the observation of a Higgs with a mass [43] of

$$M_H = 115^{+1.3}_{-0.9} \text{ GeV} .$$

7 Conclusions

Since its start in 1989 the energy range studied at LEP has more than doubled. Up to $\sqrt{s}$= 209 GeV the measurements of fermion pair production are in good agreement with the Standard Model predictions. The data taken above the Z pole allow to improve the determination of M_Z and the γ/Z interference within the S-Matrix ansatz significantly. It also allows to exclude new (contact) interactions below energy scales of 10 TeV to 20 TeV.

The cross sections for single W production, $W^+W^-$and ZZ production agree with the SM predictions as well.

From the large number of selected W^+W^-pairs the mass and width of the W boson can be directly reconstructed. The values

$$\begin{array}{rcrcl} M_W & = & 80.427 & \pm & 0.046 \text{ GeV} \\ \Gamma_W & = & 2.12 & \pm & 0.11 \text{ GeV} \end{array}$$

are in perfect agreement with the indirect determination of these quantities in fits to electroweak data. The impressive consistency between all direct measurements and indirectly determined parameters confirms the Standard Model at 1-loop level. Fits to all electroweak data profit from the recent progress in the determination of $\alpha(M_Z^2)$ and predict the mass of the Higgs boson to be

$$M_H \;=\; 88^{+60}_{-37} \text{ GeV}$$

which is consistent with the possible direct observation at LEP at $M_H \approx 115$ GeV .

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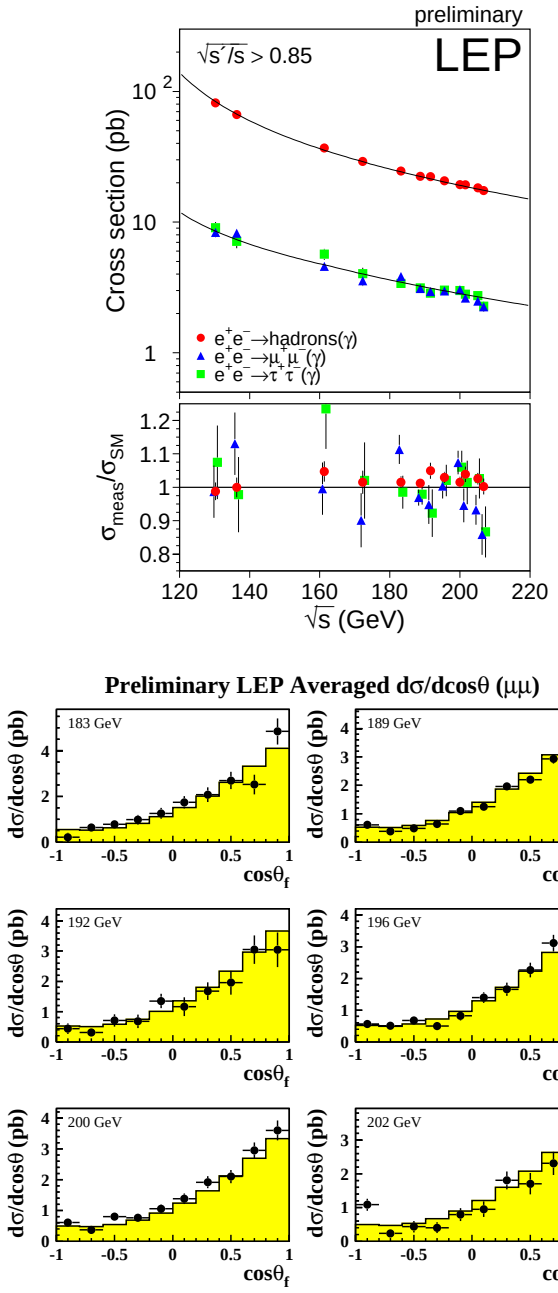


Figure 1: The measured cross sections of fermion pair production and the differential cross section for muon pair production at LEP2.

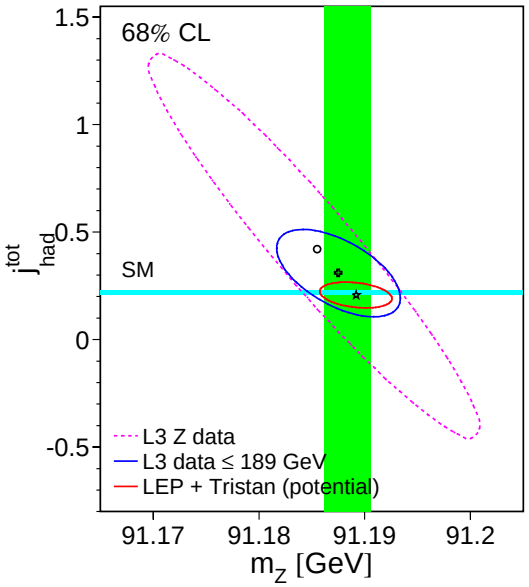


Figure 2: Contours in the (M_Z, j^{tot}_{had}) plane at 68% confidence level under the assumption of lepton universality. The dashed line is obtained from Z data only; the inclusion of 130 GeV to 189 GeV data gives the solid line. The circle (Z data) and the cross (all data) indicate the central values of the fits. The SM prediction for j^{tot}_{had} is shown as the horizontal band. The vertical band corresponds to the 68% confidence level interval on M_Z in a fit assuming the Standard Model value for γ/Z interference. The smallest contour shows the result of a fit to all LEP and TRISTAN data.

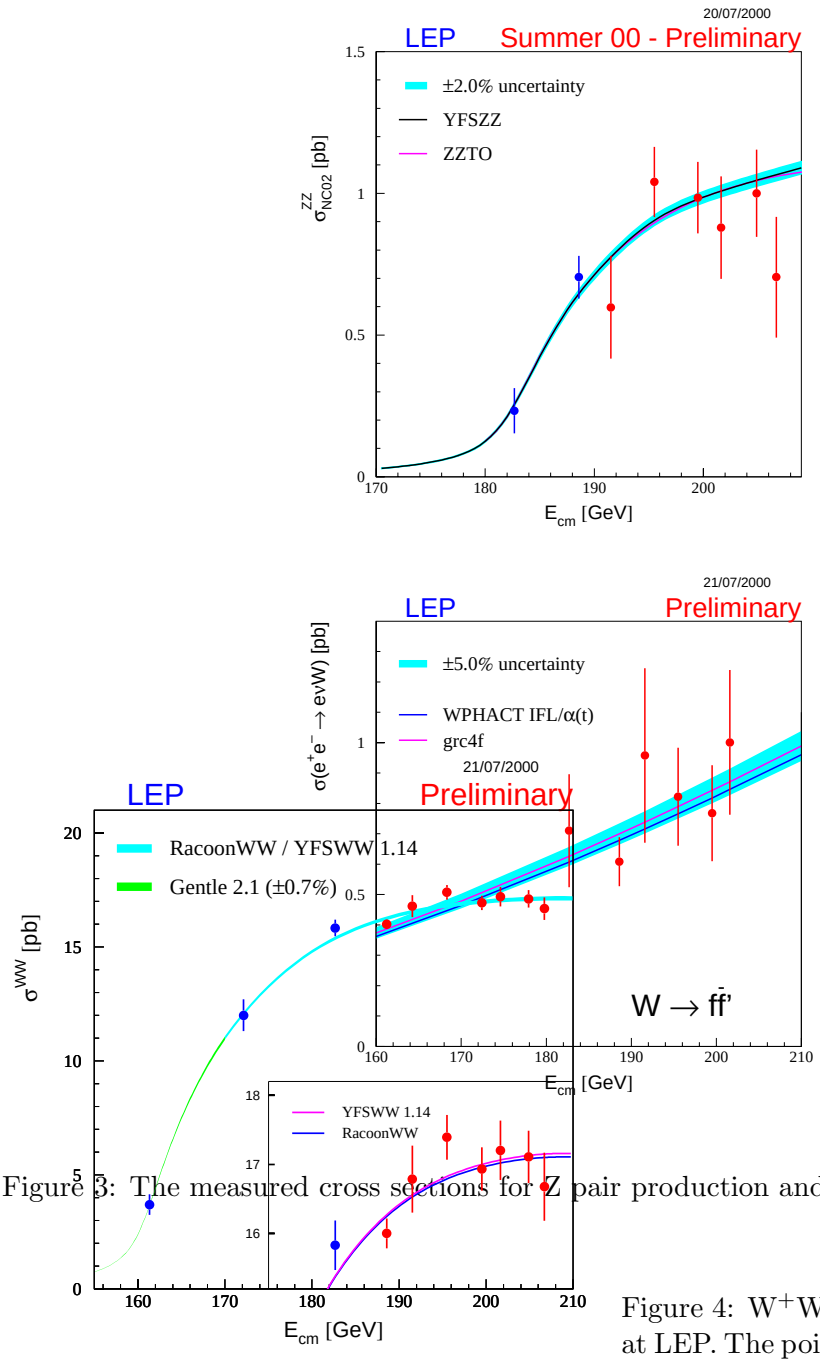
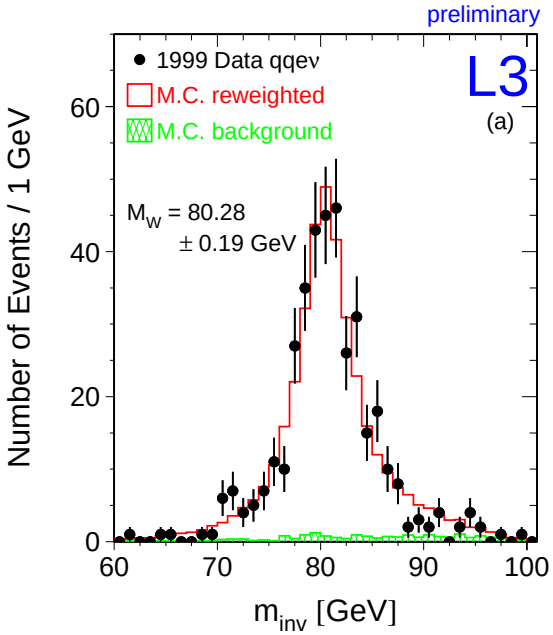
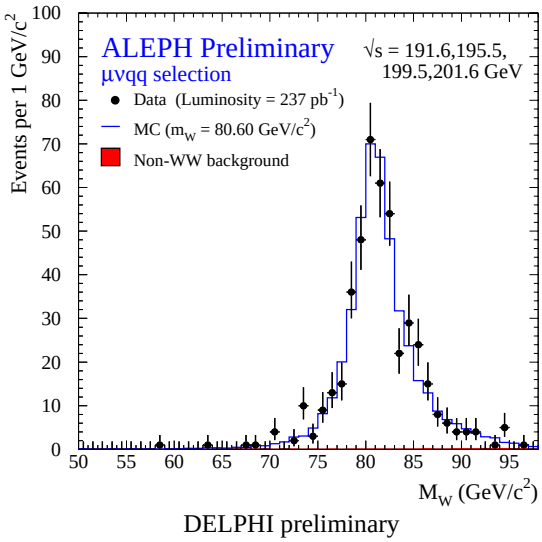


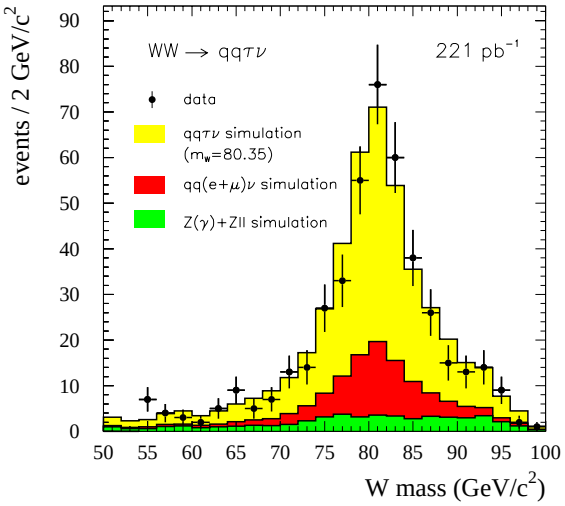
Figure 3: The measured cross sections for Z pair production and for single W production.

Figure 4: W^+W^- production cross section at LEP. The points correspond to the combined measurements of all four LEP experiments for all decay channels. The lines represent the Standard Model predictions. The Gentle program is used for $\sqrt{s} < 170$ GeV .





DELPHI preliminary



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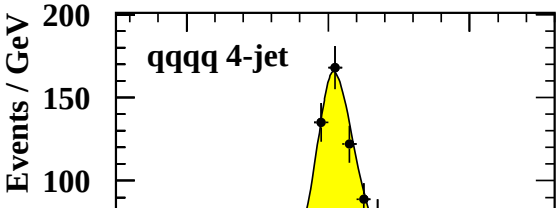

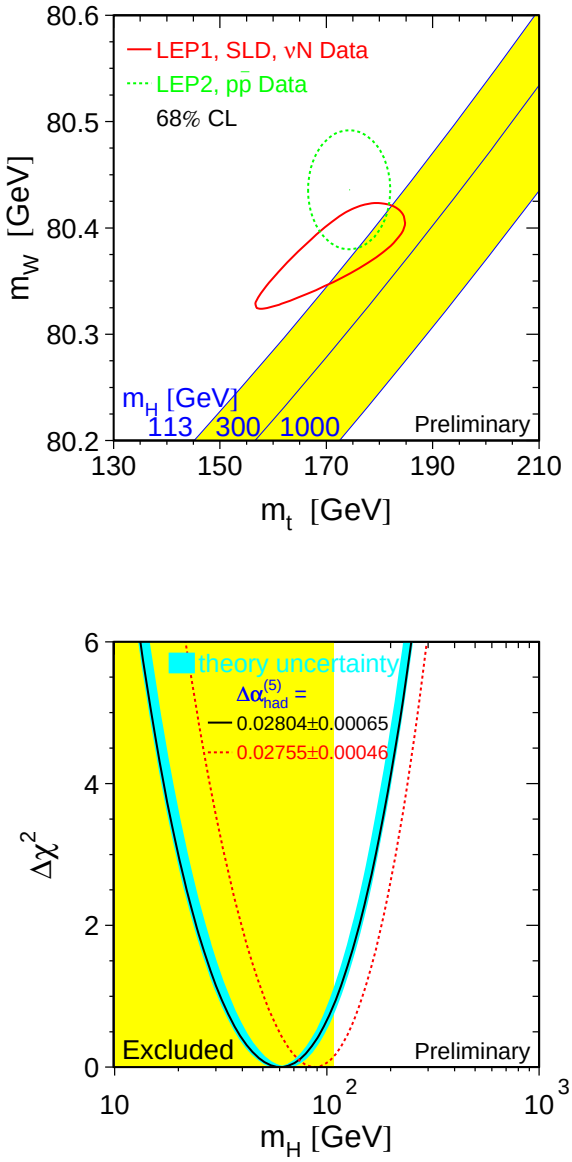

Figure 6: Left: Contours obtained from direct measurements and from a fit to electroweak precision data in the M_W-m_t plane testing the consistency of the SM. The results are compared to different values of M_H

Right: $\Delta\chi^2$ of SM fits as a function of $M_H$for different values of $\Delta\alpha^{(5)}_{had}(s)$. The blue band indicates theoretical uncertainties due to higher order corrections. Higgs masses in the shaded area are excluded by direct searches.