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Physique subatomique/*Subatomic physics*

**AVANCÉES EN PHYSIQUE DES PARTICULES :
LA CONTRIBUTION DU LEP**

ADVANCES IN PARTICLE PHYSICS: THE LEP CONTRIBUTION

The study of the W boson

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Abstract The status of the measurement of the W boson mass at LEP2 is reviewed. Properties of the W such as branching ratios into quarks and leptons and couplings to other neutral gauge bosons are reported. Four-fermion production cross sections in e^+e^- collisions are also presented. ***To cite this article: O. Buchmüller et al., C. R. Physique 3 (2002) 1173–1181.***

W boson mass / triple gauge couplings / 4-fermion processes

L'étude du boson W

Résumé Le statut de la mesure de la masse du boson W à LEP2 est passée en revue. Les propriétés du W telles que ses rapports d'embranchement en quarks et leptons et ses couplages aux autres bosons neutres sont décrites. Les mesures des sections efficaces de production de quatre fermions dans les collisions e^+e^- sont aussi présentées. ***Pour citer cet article : O. Buchmüller et al., C. R. Physique 3 (2002) 1173–1181.***

masse du boson W / couplages trilinéaires de jauge / processus à 4 fermions

1. Introduction

The success of the Standard Model (SM) of particle physics in describing all interactions of quarks and leptons at the Z resonance (LEP1) confirmed that quantum radiative corrections at the one-loop level are required. There are two classes of interesting loop corrections: the first associated with the running of α, the electromagnetic coupling constant and the second including heavy bosonic loops (W, Z). A stringent test of the existence of the latter requires a precise direct measurement of the mass of the W, (M_W) which is of fundamental importance in this model. At LEP1, M_W is inferred indirectly from the following relation using the precisely known Fermi constant, G_μ, derived from the muon lifetime:

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$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r_w+\Delta\alpha),$$

where M_Z is the Z mass. The terms $\Delta\alpha$ and Δr_w represent the electromagnetic (due mainly to light fermion loops) and the bosonic corrections respectively, amounting overall to a correction of $\sim -3\%$. The latter depends on the top mass (M_t) squared and to a smaller extent logarithmically on the Higgs boson mass ($\ln(M_H)$). From the measured value of M_t and all measurements performed at the Z resonance, the predicted value of M_W is (80.379 ± 0.023) GeV. One of the primary aims of LEP2 is to perform a direct measurement of M_W comparable or better in precision than this SM prediction. This can be used to set new constraints on m_H. Any significant deviation of M_W towards higher mass values than predicted might point to new physics.

Until 1995, W mass measurements were the exclusive domain of the $p\bar{p}$ collider experiments. The $W^\pm$ particle was first directly observed by the UA1 and UA2 experiments at CERN in 1981 [1,2] followed soon after by the Tevatron at FNAL. The combined results from UA2 [3], CDF [4,5] and D0 [6] currently measure the W mass to be (80.454 ± 0.060) GeV [7], somewhat short of the required precision. LEP2 ran just above the WW production threshold in 1996 at a centre-of-mass (CM) collision energy of 161 GeV and this energy increased every year to reach 207 GeV in 2000. By measuring the properties of each W-pair event and using the precise knowledge of the e^+e^- collision energy, LEP2 has been the laboratory where this vital test of the SM can be effectively pursued.

A second important test of the SM is the structure of the triple gauge couplings (TGC: $WW\gamma$ and WWZ couplings). They play a direct role at the tree level in the W-pair cross section in contrast to the Z resonance where they enter only through loops. The non-Abelian (Yang–Mills) nature of the TGC can be established by studying the differential cross sections and topology of the W-pair events in detail.

At the time of this report, analyses of LEP2 data are not finalised, hence all results presented in this report are still *preliminary*.

2. W and four-Fermion production at LEP2

At LEP W bosons are predominantly produced in pairs through the reaction $e^+e^- \to W^+W^-$, with each of the W's subsequently decaying either hadronically ($q_1\bar{q}_2$), or leptonically ($\ell^-\bar{\nu}_\ell,\ \ell = e, \mu, \tau$). This yields three possible four-fermion final states, hadronic ($q_1\bar{q}_2q_3\bar{q}_4$), semi-leptonic ($q_1\bar{q}_2\ell\bar{\nu}_\ell$) and leptonic ($\ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$), with branching fractions of 45%, 44% and 11% respectively (Figs. 1 and 2).

For precise measurements, complete four-fermion calculations are needed. For the simple channel $e^+e^- \to u\bar{d}e^-\bar{\nu}_e$, there are twenty processes that can contribute to this final state. In total more than 3000 diagrams are needed to account for the final states compatible with a W^+W^-.

Unlike Z production at LEP1, WW production ($\sigma \sim 15$ pb) is not the main channel. The majority of selected events with high energy deposited in the detector comes from two fermion final states. For the WW analysis to four quarks, the huge background originating from the $e^+e^- \to q\bar{q}(\gamma)$ channel ($\sigma \sim 100$ pb) has to be reduced. Sophisticated procedures, based on Neural Networks for example, have been developed to select W-pair events.

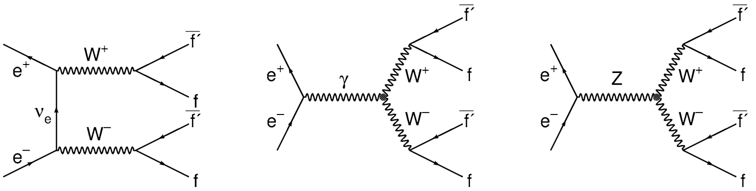

Figure 1. Lowest order processes contributing to a W^+W^- final state in e^+e^- annihilations.

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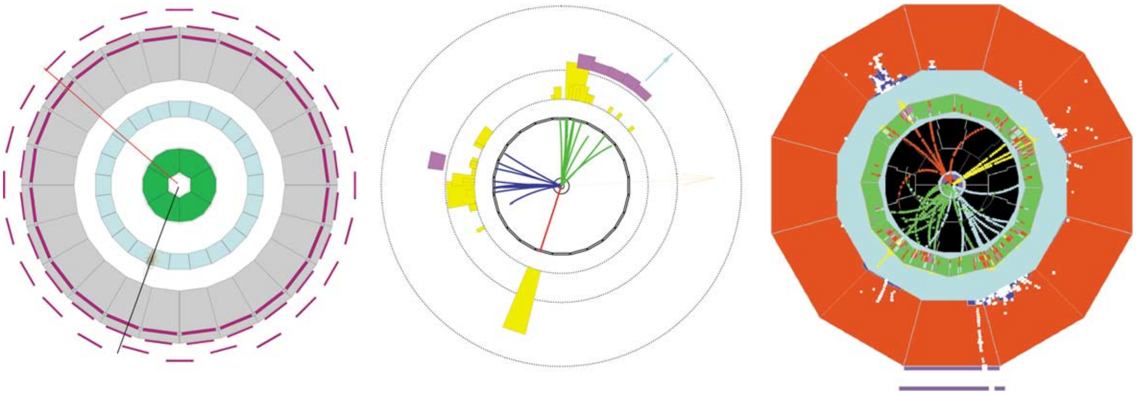

Figure 2. Event displays corresponding to the three topologies of the final states: $\ell\nu\ell\nu$ (left), $\mathrm{q\bar{q}}\ell\bar{\nu}_\ell$ (center) and $\mathrm{q\bar{q}q\bar{q}}$ (right).

Table 1. W branching ratios measurement at LEP2.

Channel	$\mathrm{W} \to \mathrm{e}\nu_\mathrm{e}$	$\mathrm{W} \to \mu\nu_\mu$	$\mathrm{W} \to \tau\nu_\tau$	$\mathrm{W} \to \mathrm{q_1\bar{q_2}}$
Branching ratio (%)	10.54 ± 0.17	10.54 ± 0.16	11.09 ± 0.22	67.92 ± 0.27

2.1. W decay branching fractions

The LEP collaborations use separate selections to identify the three topologies and the $\ell\nu\ell\nu$ and $\mathrm{q\bar{q}}\ell\bar{\nu}_\ell$ events are further classified according to their observed lepton type. Thus, the $\mathrm{W^+W^-}$ events are subdivided into ten possible final states ($6 \times \ell\nu\ell\nu$, $3 \times \mathrm{q\bar{q}}\ell\bar{\nu}_\ell$ and $1 \times \mathrm{q\bar{q}q\bar{q}}$). Each experiment has recorded $\sim 12\,000$ W-pair events with efficiencies and purities in each channel of more than 80%.

From these ten sub-channels, W branching ratios are extracted assuming that all W's decay to these 4 channels. To first order, precise knowledge of the luminosity is not required since W's are pair produced. Table 1 summarises the present results; the hadronic branching ratio is determined assuming lepton flavour universality, confirmed by data within statistical error. These results for the leptonic and hadronic branching ratios are consistent with their Standard Model expectations of 10.83% and 67.51% respectively [8]. The two-by-two comparison of these branching fractions constitutes a test of lepton universality in the decay of on-shell W bosons at the level of 2.9% (see the contribution by Rougé and Tanaka [9]).

The Cabibbo–Kobayashi–Maskawa (CKM) matrix transforms the three families of quarks from mass eigenvectors to eigenvectors of weak decays. It describes the amplitude of the vertex $\mathrm{q_1q_2W}$. It is related to the branching ratio by $Br(W \to \mathrm{q_1\bar{q_2}}) \propto |V_{\mathrm{q_1q_2}}|^2$. Since the top quark is heavier than the W boson, the CKM terms containing top are not directly accessible through W branching ratios. The $|V_{cs}|$ term is the least well known of the second generation. The W decay branching fractions give access to this parameter $|\mathrm{V}_{cs}| = 0.996 \pm 0.013$. It had been previously measured using the branching ratio of $B \to D\ell\nu$ which gave $|V_{cs}| = 1.04 \pm 0.16$.

2.2. W-pair production cross section

WW production cross section has been measured at each CM energy for the three different topologies. The total cross section is usually derived by assuming Standard Model values for the W branching ratios, although this assumption hardly change the prediction. The results, shown in Fig. 3, are in striking agreement with the electroweak gauge theory, requiring the contribution of the three amplitudes discussed above to be present. Indeed, only ν_e exchange would lead to a diverging cross section, while the γ and Z contributions stabilize the cross section, as confirmed by the measurements.

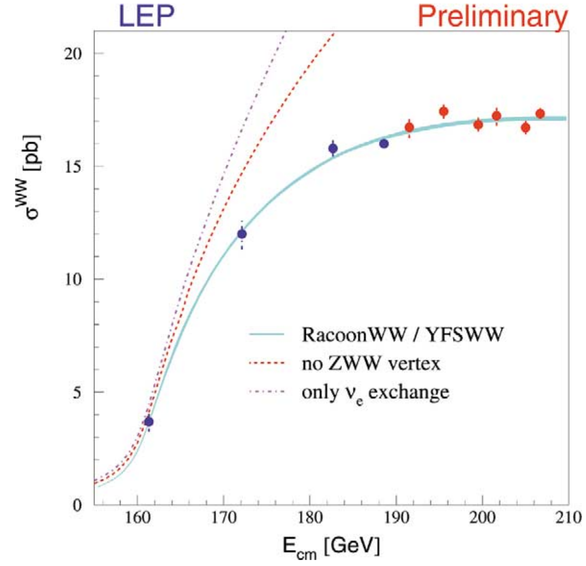

Figure 3. Measurements of the W-pair production cross section. The shaded area represents the uncertainty on the theoretical predictions, estimated to be ±2% for $\sqrt{s} < 170$ GeV and ranging from 0.7 to 0.4% above 170 GeV.

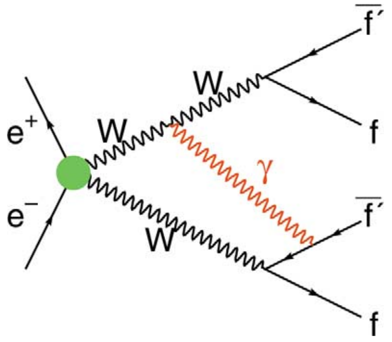

Figure 4. Example of one of the many possible interactions between W's and their final states.

The cross section is now theoretically computed to better than 0.5% level. In 1996, the accuracy of the prediction was at the level of $\approx 2\%$. A large amount of work from theoreticians has reduced the uncertainty by the inclusion of quantum corrections between W's and their final states, such as the diagram illustrated in Fig. 4. The inclusion of these extra contributions not only reduces the uncertainty on the total cross section but also reduces the absolute value by 2.5%. Currently, the ratio of theoretical prediction to experimental measurement of the W-pair production cross section is determined to be: $0.998 \pm 0.006(\mathrm{stat.}) \pm 0.007(\mathrm{syst.})$.

2.3. Other 4-fermion processes

Other 4-fermion cross sections have also been measured. Among these are the Z-pair and single W production ($\mathrm{e}^+\mathrm{e}^- \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\mathrm{W}^+, \mathrm{e}^+\nu_\mathrm{e}\mathrm{W}^-$) cross sections. At CM energies exceeding twice the Z boson mass, pair production of Z bosons is kinematically allowed and in fact represents one of the main backgrounds in the direct search for the Higgs boson. The production of single W provides information on the WWγ coupling. The measurements are shown in Fig. 5 as a function of the LEP CM energy, where they are compared to theoretical predictions. The data do not show any significant deviation from expectations.

3. Electroweak gauge boson self couplings

One of the fundamental predictions of the electroweak theory is the self-coupling of the gauge bosons W, Z and γ due to the non-Abelian nature of the gauge group. In general, there are seven unique Lorentz invariant couplings for each of the WWV vertex, where V denotes the neutral vector bosons γ and Z. Assuming electromagnetic gauge invariance, charge conjugation and parity conservation, and using also constraints from low energy data, reduces the number of couplings from 14 in the most general case to three $\{g_1^Z, \kappa_\gamma, \lambda_\gamma\}$ [10]. In the framework of the SM they are predicted to be $g_1^Z = \kappa_\gamma = 1,\ \lambda_\gamma = 0$.

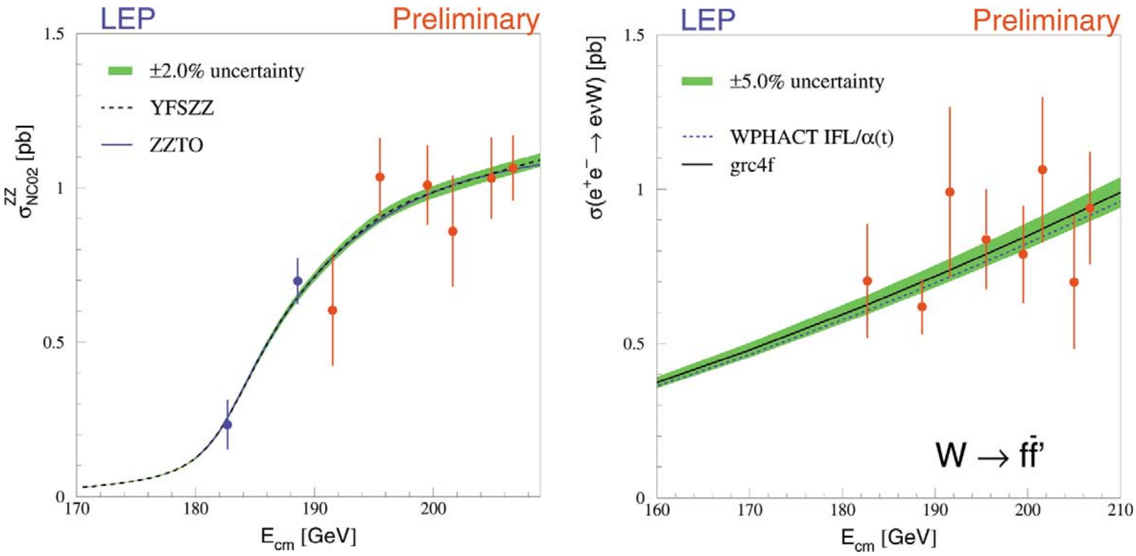

Figure 5. Measurements of the Z-pair (left) and single W (right) production cross section. The shaded areas represent the uncertainties on the predictions.

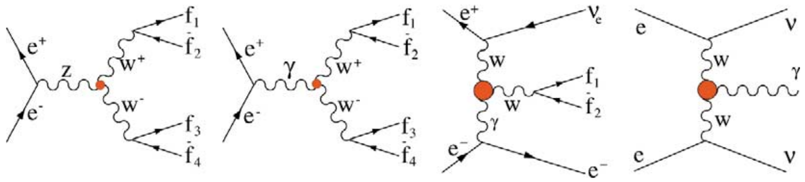

Figure 6. Processes sensitive to triple gauge boson couplings WW production (left), single-W production (center) and single-γ production (right).

The photonic couplings λ_γ and κ_γ are related to the magnetic and electric properties of the W-boson. One can write the lowest order terms for a multipole expansion describing the W–γ interaction as a function of λ_γ and κ_γ. For the magnetic dipole moment μ_W and the electric quadrupole moment q_W one obtains:

$$\mu_W = \frac{\mathrm{e}}{2M_W}(1+\kappa_\gamma+\lambda_\gamma),$$

$$q_W = -\frac{\mathrm{e}}{M_W^2}(\kappa_\gamma-\lambda_\gamma).$$

Deviations of κ_γ and λ_γ from their SM values would therefore prove the presence of anomalous electromagnetic moments of the W boson and thus indicate the presence of new physics.

At LEP2 these coupling parameters are measured through the following processes (Fig. 6):

- $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to$ 4 fermions gives access to g_1^Z, κ_γ and λ_γ,
- $\mathrm{e^+e^-} \to \mathrm{We}\nu_\mathrm{e}$ is sensitive to κ_γ,
- $\mathrm{e^+e^-} \to \nu_\mathrm{e}\bar{\nu}_\mathrm{e}\gamma$ is related to κ_γ.

The results shown in Table 2 have been derived using not only information from the production cross section of the above mentioned processes but also from distributions of kinematic variables like the polar angle of the W or the $\mathrm{W}^\pm$ helicities when available. All three measurements of the coupling constants are in agreement with their SM predictions.

Table 2. The combined 68% C.L. errors and 95% C.L. intervals obtained combining the results from the four LEP experiments. In each case the parameter listed is varied while the other two are fixed to their Standard Model values. Both statistical and systematic errors are included.

Parameter	68% C.L.	95% C.L.
g_1^Z	$0.990^{+0.023}_{-0.024}$	[0.944, 1.035]
κ_γ	$0.896^{+0.058}_{-0.056}$	[0.786, 1.009]
λ_γ	$-0.023^{+0.025}_{-0.023}$	[−0.069, 0.026]

4. W-boson mass and width measurements at LEP2

Two main methods have been employed to measure M_W at LEP2. The first exploited the sensitivity of the W^+W^- production cross section to M_W for CM energies close to threshold. In 1996, each of the four LEP experiments collected about 10 pb^{-1} of data at 161 GeV, resulting in a combined determination of the W mass of $M_W = (80.40 \pm 0.20 \pm 0.03)$ GeV. The quoted uncertainties are the total experimental and LEP beam energy errors respectively. The second method measures M_W by direct reconstruction of the invariant mass of the W decay products. This method has taken over above threshold where the cross section is much larger (∼16 pb) and no longer sensitive to M_W. Since most of the LEP2 data have been collected at CM energies well above threshold (∼700 pb^{-1}/experiment), the mass and width measurements are derived almost entirely from the direct reconstruction method.

This method proceeds in three steps:
(i) selection of $W^+W^- \to f\bar{f}f'\bar{f}'$ events;
(ii) reconstruction of invariant masses for each event; and
(iii) extraction of M_W from the accumulated mass distributions.

Only the three $q\bar{q}\ell\bar{\nu}_\ell$ and the $q\bar{q}q\bar{q}$ channels are used by all experiments; $\ell\nu\ell\nu$ events are comparatively rare and contain little information. Background contamination is kept below 15% for the $q\bar{q}q\bar{q}$ channel and at a few % level for the other channels.

The quark pairs from the hadronically decaying W's in each event are recognised as two 'jets' of hadrons by clustering algorithms. It is not possible to unambiguously identify the charge of quark pairs from their corresponding jets. This gives rise, in the $q\bar{q}q\bar{q}$ channel, to an ambiguity in the pairing of the four reconstructed jets. The most likely combination evaluated from the event topology is correct in ∼90% of cases.

For the direct reconstruction of the W mass from its decay products the precise knowledge of the e^+e^- collision energy is very beneficial. Using a kinematic fit to force the events to fulfil energy and momentum conservation leads to a significant improvement in the resolution of the W mass. These fits require detailed input information, provided by Monte Carlo simulations of the detector performance, on the errors and biases in the constructed jet and lepton 4-momenta which are adjusted on high statistics Z data from LEP1. The effect of photon radiation from the incoming e^+e^- beams and its uncertainty is incorporated in the total systematic uncertainty error on M_W. Fig. 7 shows examples for the reconstructed mass distributions of $q\bar{q}q\bar{q}$ and $q\bar{q}\ell\bar{\nu}_\ell$ events.

The four LEP experiments employ different techniques to extract M_W and Γ_W but basically they all rely on fitting using maximum likelihood methods, comparing data to fully simulated events. The most common procedure is 'Monte Carlo reweighting' where the measured mass distribution is fitted to a fully simulated prediction built from a large sample of signal and background events which have been subjected to identical analysis criteria. These events have been generated with fixed M_W and Γ_W close to the expected values. This prediction can then be adjusted for different M_W's (and Γ_W's) by 'reweighting' the individual generated signal events according to their topology; thus avoiding massive full re-simulations. The final

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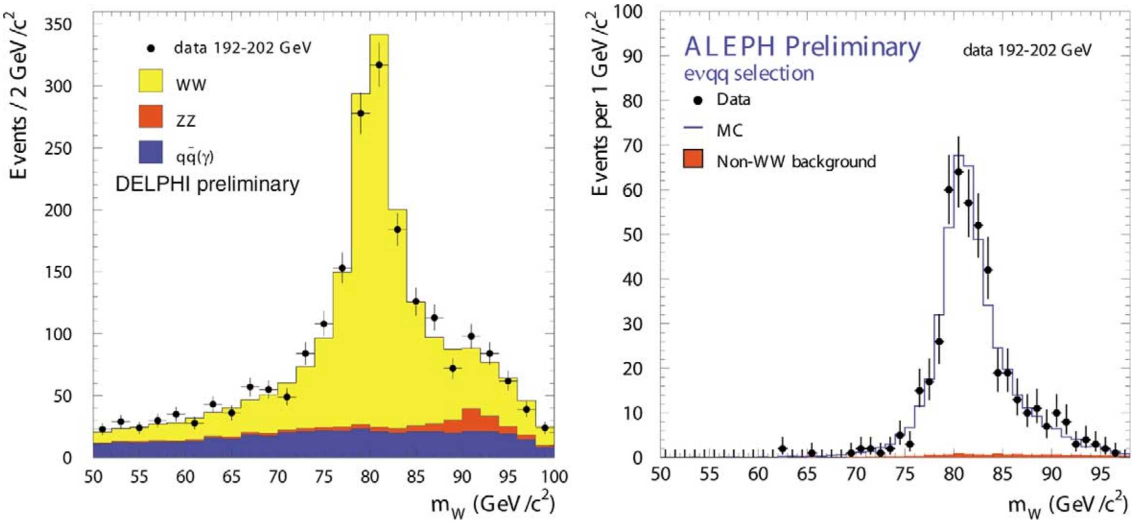

Figure 7. Examples for reconstructed mass distributions for the $q\bar{q}q\bar{q}$ (left) and $q\bar{q}\ell\bar{\nu}_\ell$ (right) channels.

likelihood fits have become more sophisticated and multi-dimensional in an effort to extract the maximum statistical power out of the data.

4.1. Final state interactions

Due to the relatively short distance separating the decay vertices of the W bosons produced in e^+e^- annihilation ($\sim$0.1 fm) compared to the typical hadronisation scale (1 fm) it is possible that partially overlapping hadronic systems from different W bosons are interacting. These so-called Final State Interactions (FSI) would undermine the hypothesis of two independent W bosons decays and lead to a change of the kinematic properties of the event. There are two different types of Final State Interactions to be considered.

The first type of interaction is Colour Reconnection (CR). The original colour singlets $W \to q_1\bar{q}_2$ and $W \to q_3\bar{q}_4$ could rearrange in alternative $q_1\bar{q}_4$ and $q_3\bar{q}_2$ colour singlets via hard gluon exchange. This rearrangement probability can be computed. It is proportional to $(\alpha_s^2\Gamma_W)/(N_c^2 M_W)$, where α_s is the coupling constant of the strong interaction, Γ_W the width of the W and N_c the number of colours; it is less than 10^{-3}, hence very unlikely. However, CR might occur at the non-perturbative stage of the hadronisation cascade. In this cascade, colour fluxes between quark and gluons from the two fragmenting W systems may overlap. If so, there is some probability for CR to occur in this overlap region. Only phenomenological models are able to simulate this non-perturbative reconnection effect. According to these models, CR results in some depletion and/or enhancement of soft particles in specific phase space regions leading to a bias in the reconstruction of the W decay products. Depending on the model used to simulate the CR effect the bias in W mass extracted in the $q\bar{q}q\bar{q}$ channel may vary between 0 and 90 MeV.

The second type of interaction is Bose–Einstein correlations (BEC). This effect is quantum mechanical in origin and manifests itself as an enhancement of the production of identical bosons close in phase space. BEC have been observed for two or more identical bosons ($\pi\pi$, KK, etc,...) produced in Z decays and single W (intra-W BEC) decays. Additional correlations between particles coming from different Ws (inter-WW BEC) might exist inducing a possible shift in the reconstructed W mass. BEC effects are usually studied (Fig. 8) in terms of a two-particle correlation function $\rho(Q)$ where Q is the 4-momentum difference between two particles: $Q^2 = -(p_1 - p_2)^2$. Similarly to the CR scenario, all predictions for BEC's are highly

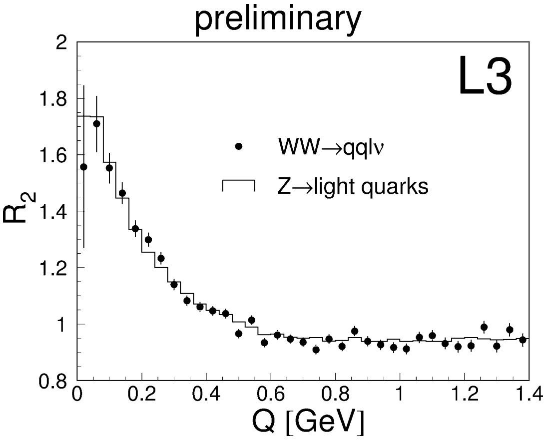

Figure 8. Ratio of two particle correlation function: $R_2(Q) = \rho(Q)/\rho_0(Q)$, where ρ_0 is the expectation in the absence of BEC; measured in W and Z decays.

model dependent. According to the available models, BEC effects could lead to W mass shifts between 0 and 100 MeV in the $q\bar{q}q\bar{q}$ channel.

Analyses are currently underway, and preliminary results indicate that CR models leading to a large (>50 MeV) mass shift are unlikely, similarly inter-WW BEC have not been observed by any experiment at LEP. One way to check that large FSI effects are not present is to compare the W mass measured in the $q\bar{q}q\bar{q}$ channel to that measured in the $q\bar{q}\ell\bar{\nu}_\ell$ channel. The difference is found to be $\Delta m_W(q\bar{q}q\bar{q} - q\bar{q}\ell\bar{\nu}_\ell) = +9 \pm 44$ MeV which is consistent with no final state interactions. A conservative systematic error on the W mass measurement in the $q\bar{q}q\bar{q}$ channel of 47 MeV (40 for CR and 25 for inter-BEC) is currently assigned. It is likely to be reduced in the near future.

4.2. Results

So far, only data up to 189 GeV have been published. All results based on the full datasets spanning 161–207 GeV CM energies are preliminary. The following are taken from those presented in 2002 [11]. The LEP2 combined result is:

$$m_W = (80.450 \pm 0.026_{\text{stat.}} \pm 0.022_{\text{syst.}} \pm 0.013_{\text{FSI}} \pm 0.017_{\text{LEP}})\ \text{GeV}.$$

If Γ_W is fitted simultaneously rather than assuming the SM value, the mass is essentially unchanged and an average value of (2.150 ± 0.091) GeV is found consistent with SM expectations. The total error in M_W of 39 MeV is composed of 26 MeV statistical and 30 MeV systematic uncertainty summed in quadrature; indicating that a substantial improvement over the $p\bar{p}$ colliders is in prospect. However, matching the uncertainty in the indirect measurement from the SM fits of 23 MeV will be a considerable challenge.

Currently, the total error in the $q\bar{q}q\bar{q}$ channel is much higher than the combined $q\bar{q}\ell\bar{\nu}_\ell$ channels which is mainly due to the systematic uncertainties inherent in this channel from FSI effects.

$$m_W(W^+W^- \to q\bar{q}\ell\bar{\nu}_\ell) = (80.448 \pm 0.033_{\text{stat.}} \pm 0.028_{\text{syst.}})\ \text{GeV},$$
$$m_W(W^+W^- \to q\bar{q}q\bar{q}) = (80.457 \pm 0.030_{\text{stat.}} \pm 0.054_{\text{syst.}})\ \text{GeV}.$$

This has the effect of ‘deweighting’ this channel to just 27% in the average even though the statistical errors are comparable. A major benefit would be achieved by reducing this inequality so that both channels contribute with approximately equal weighting. In this case, the statistical error would diminish to 22 MeV. The other expected improvement is in the accuracy of the LEP2 beam energies which currently contribute 17 MeV to the final result.

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5. Conclusions

The study of the W boson is now the main activity in the LEP community 18 months after the closure of the LEP collider. This continuing effort is devoted to a measure of the W mass and the self-couplings of the gauge bosons as precisely as possible. Such stringent tests of the Standard Model complement those performed already and are not expected to be improved upon for many years.

Currently, the W boson mass is measured at LEP2 with a precision of 39 MeV. The overall systematic uncertainty dominates over the statistical error due to our present lack of understanding of the LEP beam energies and final state interactions between the W decay products. Ultimately, it is expected that a total error of 30 MeV is within reach. The value of M_W reported to date is in excellent agreement with the $p\bar{p}$ colliders yielding a world average value of (80.451 ± 0.033) GeV [11]. This value lies within two standard deviations of the indirect SM prediction which is (80.379 ± 0.023) GeV from the latest fits to Z data and including M_t measured at the Tevatron.

The impact of the precise measurement of M_W is discussed in the contribution by Olchevski and Winter [12]. The present value leads to an indirect determination of the Higgs boson mass which turns out to be quite low, $(\sim 20^{+50}_{-20})$ GeV, compared to the limit from the direct search as given in the contribution by Janot and Kado [13]. In view of this potential problem, it is important that all systematic effects in the W studies within and between the four LEP experiments are exhaustively examined to a satisfactory conclusion.

The self-couplings of the electroweak gauge bosons, one of the key predictions of the $SU(2) \otimes U(1)$ structure of the theory, have been studied by searching for any discrepancy between the measured reduced couplings, $\{g_1^\mathrm{Z}, \kappa_\gamma, \lambda_\gamma\}$ and their predicted values in the SM. No significant deviations have been observed. The most precisely measured coupling is g_1^Z now known to 2%.

The measurements of the WW total cross section as a function of CM energy have emphatically demonstrated the existence of the triple gauge couplings. In addition, the unexpected accuracy in the measurements compelled the theorists to incorporate full corrections to the doubly-resonant WW pair production diagrams. These new predictions describe the data to better than a % level. These large sophisticated theoretical programs, taking into account all 4-fermion diagrams, will be needed by the next linear colliders.

Finally, the ZZ cross section has been measured and found to agree with SM expectations. This channel constitutes the principal background to the Higgs search in the Z mass region and the prediction from the SM had been assumed.

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