Direct measurement of the W boson mass in $e^+ e^-$ collisions at LEP
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Summary

In the press release for the Nobel Prize awarded to the Dutch high-energy physicists Gerard 't Hooft and Martinus Veltman in 1999, the Nobel Committee referred to the agreement between theoretical calculations made possible by their work and recent precise measurements of W and Z particle properties at LEP. In fact, the availability of a quantitative theoretical framework makes it meaningful to measure the free parameters of the theory with great precision, in order to test the theory for consistency and completeness and to search for phenomena beyond. One of these parameters is the mass of the W particle, the measurement of which is the main topic of this thesis.

The LEP collider at CERN in Geneva is the largest particle accelerator built to date. Thanks to its large circumference and the use of super-conducting accelerating cavities, a technology not yet established at the time of LEP’s conception, LEP is the most powerful accelerator for electrons and their anti-particles, positrons. Colliding electrons and positrons yields clean events with well-defined kinematical properties, allowing precision measurements. During the years 1996 to 2000 the collision energy was larger than the threshold for the production of pairs of W bosons. In this period each of the four LEP experiments recorded about 10,000 W pair events. Since W particles are unstable and have a very short lifetime, only the decay products of the boson pairs were detected. From the measured invariant mass of the decay products, the mass of the W boson can be determined with high precision.

The analysis presented here is based on the data recorded by the DELPHI detector in the years 1996-1998, corresponding to about one third of the final statistics. From this data sample, the following W mass was measured:

\[ m_W = 80.339 \pm 73 \text{ (stat)} \pm 47 \text{ (syst)} \text{ MeV/c}^2 \]

where the first uncertainty is statistical and the second uncertainty accounts for possible systematic effects. In addition to the mass, also the natural mass spread (width) of the W bosons was measured. This width is related to the very short lifetime of the W bosons via the Heisenberg uncertainty principle, and was measured to be

\[ \Gamma_W = 2.295^{+173}_{-164} \text{ (stat)} \pm 78 \text{ (syst)} \text{ MeV/c}^2 \]

Finally the difference between the W$^+$ and W$^-$ mass, predicted to be zero, has been measured for the first time at LEP, giving the following result:

\[ \frac{m_{W^+} - m_{W^-}}{m_W} = -0.013 \pm 0.011 \text{ (stat)} \pm 0.002 \text{ (syst)} \]

All the above results are in agreement with existing direct measurements and predictions in the framework of the Standard Model.
These results will be superseded by the final analysis of all DELPHI data, which is currently in progress. Therefore the most valuable and long lasting contribution of the work presented here is the development of the new ideas and analysis methods.

The Ideogram approach aims at including the maximum attainable amount of information from each recorded event in order to minimise the statistical uncertainty. New ideas include a 5-jet treatment for events with 5 jets, the combination of different jet clustering algorithms, the inclusion of all possible jet pairings and the full description of the mass information of both W bosons in each event. The construction of a likelihood curve for each event has turned out to be a useful innovation allowing for further statistical analysis, for example by means of the Jackknife technique.

In addition to the statistical error, the systematic uncertainty on the measurement plays a significant role. In order to obtain a good understanding of the measurement and have confidence in the results, a detailed study of the systematic effects is presented. The study covers a wide range of possible sources of systematic errors, including an imperfect knowledge of the detector, the accelerator, and of the physics models used. In order to allow a model-independent investigation of possible systematics related to the hadronic decay of W bosons into jets, a novel technique is introduced known as the Mixed Lorentz-Boosted $Z^0$ technique. This method is shown to allow a study of fragmentation effects and part of the detector systematics with a precision of 5 MeV/c$^2$ or better.

The understanding of the statistical and systematic aspects of the W-mass analysis has almost reached the level required for an experimental determination of the W mass at the same level of precision as the Standard Model prediction, based on a global fit using all indirect measurements. Two systematic uncertainties, however, need further investigation: the LEP beam energy scale and the effects of final state cross-talk in the fully hadronic channel. These studies are expected to be completed in the coming years. A final uncertainty on the combined W mass measurement of all four LEP experiments better than 30 MeV/c$^2$ is within reach. Such a result will help to further constrain the allowed range for the mass of the so far elusive Higgs boson, and will possibly remain the most precise measurement of the W mass, a fundamental constant of nature, for many years to come.