Measurement of the W boson mass and width with the L3 detector

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Chapter 7

Conclusion and outlook

The previous chapters described the analysis of the W mass measurement. A summary of the obtained results will be presented in this chapter. The measurement will be compared with results of other experiments and their combination.

The following sections will give a brief prospective to future experiments and expectations in the framework of the determination of the W properties.

7.1 Results

The results presented in this thesis are performed on the data collected by the L3 detector during the period from 1998 to 2000. The centre-of-mass energy is increased from $\sqrt{s} = 189$ GeV to 208 GeV during this period. The total integrated luminosity collected by the L3 detector at these energies amounts to $629.3 \text{ pb}^{-1}$.

The W mass and width analysis is performed on the decay of W pairs to the semi-leptonic channels $qq\nu\bar{\nu}, qq\mu\bar{\nu}$ and $qq\tau\bar{\nu}$ and the fully hadronic channel. A likelihood method with a Monte Carlo re-weighting procedure is used, as is described in chapter 5, to extract $M_W$ and $\Gamma_W$ and their statistical errors.

Chapter 6 describes the uncertainties originating from different sources for each channel.

A $\chi^2$ minimisation technique [59] is used to average the individual measurements. The correlations are taken into account by assuming that the measurements are fully correlated or fully uncorrelated in the covariance matrix. For the semi-leptonically decaying W pairs the following mass and width results are obtained:

$$M_W = 80.292 \pm 0.075(\text{stat}) \pm 0.040(\text{syst}) \text{ GeV}. \quad (7.1)$$

$$\Gamma_W = 2.36 \pm 0.18(\text{stat}) \pm 0.05(\text{syst}) \text{ GeV} \quad (7.2)$$

The same analysis procedure is followed for the fully hadronic channel, which results into:

$$M_W = 80.342 \pm 0.066(\text{stat}) \pm 0.079(\text{syst}) \text{ GeV}, \quad (7.3)$$

$$\Gamma_W = 2.18 \pm 0.17(\text{stat}) \pm 0.13(\text{syst}) \text{ GeV}. \quad (7.4)$$
Combining these measurements by $\chi^2$ minimisation including the complete systematic errors for which the individual numbers are given in chapter 6 yields:

$$M_W = 80.323 \pm 0.047\,(\text{stat}) \pm 0.051\,(\text{syst}) \text{ GeV}, \quad (7.5)$$

$$\Gamma_W = 2.27 \pm 0.12\,(\text{stat}) \pm 0.07\,(\text{syst}) \text{ GeV}. \quad (7.6)$$

## 7.2 Mass comparison

The W properties are also measured at LEP by the other three experiments: ALEPH, DELPHI and OPAL. In addition, a complementary study is done at L3, which is used in the final combination of the LEP mass measurement and width measurement.

The measurements done in 1996 at the centre-of-mass energy close to the W pair production threshold at $\sqrt{s} = 161 \text{ GeV}$ exploit the fact that the cross section is sensitive to the W boson mass. This analysis is called the threshold analysis in contrast to the analysis performed at the higher energies, using the mass spectrum to determine the mass and width. Based on the data of [68–71] a summary of the results from the four LEP collaborations is shown in table 7.1.

Table 7.1: W mass measurement at the production threshold at $\sqrt{s} = 161 \text{ GeV}$. The errors include statistical and systematic contributions.

<table>
<thead>
<tr>
<th>Threshold analysis</th>
<th>experiment</th>
<th>$M_W$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ALEPH</td>
<td>80.14 ± 0.35</td>
</tr>
<tr>
<td></td>
<td>DELPHI</td>
<td>80.40 ± 0.45</td>
</tr>
<tr>
<td></td>
<td>L3</td>
<td>80.80$^{+0.48}_{-0.42}$</td>
</tr>
<tr>
<td></td>
<td>OPAL</td>
<td>80.40$^{+0.36}_{-0.33}$</td>
</tr>
</tbody>
</table>

At energies higher than the threshold energy, $\sqrt{s} = 172 - 208 \text{ GeV}$, the data is analysed through the direct reconstruction of the W invariant mass spectrum. The LEP W mass result is split into a $qg\ell\nu$ and $qqqg$ part. Table 7.2 summarises the obtained results per experiment [66]. The third column in this table gives the combination of both decay channels for the individual experiments.

Studies have been performed which have shown that the four experiments are equally sensitive to colour reconnection effects (as shown in figure 6.4) and Bose-Einstein correlations [66]. Therefore, a common value is used for FSI in calculating the combinations.

The combination of all direct reconstructions of the W boson mass of the four LEP collaborations yields

$$M_W(qg\ell\nu) = 80.411 \pm 0.032\,(\text{stat.}) \pm 0.030\,(\text{syst.}) \text{ GeV}, \quad (7.7)$$

$$M_W(qqqq) = 80.420 \pm 0.035\,(\text{stat.}) \pm 0.101\,(\text{syst.}) \text{ GeV}. \quad (7.8)$$
Table 7.2: The mass measurement of the W boson for centre-of-mass energies from 172 GeV to 208 GeV for the individual collaborations. The result is split into semi-leptonic, fully hadronic channel and the combined value. The results from ALEPH and OPAL include the \( \ell \ell \nu \nu \) channel in the \( qq\ell \nu \) results.

<table>
<thead>
<tr>
<th>experiment</th>
<th>( MW \rightarrow qq\ell \nu ) [GeV]</th>
<th>( MW \rightarrow qqqq ) [GeV]</th>
<th>combined [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>80.375 ± 0.062</td>
<td>80.431 ± 0.117</td>
<td>80.385 ± 0.058</td>
</tr>
<tr>
<td>DELPHI</td>
<td>80.414 ± 0.089</td>
<td>80.374 ± 0.119</td>
<td>80.402 ± 0.075</td>
</tr>
<tr>
<td>L3</td>
<td>80.314 ± 0.087</td>
<td>80.485 ± 0.127</td>
<td>80.367 ± 0.078</td>
</tr>
<tr>
<td>OPAL</td>
<td>80.516 ± 0.073</td>
<td>80.407 ± 0.120</td>
<td>80.495 ± 0.067</td>
</tr>
<tr>
<td>combined</td>
<td>80.411 ± 0.044</td>
<td>80.420 ± 0.107</td>
<td>80.412 ± 0.042</td>
</tr>
</tbody>
</table>

The combined mass value for all channels is:

\[
MW(combined) = 80.412 \pm 0.042 \text{ GeV.} \tag{7.9}
\]

The inclusion of the threshold measurement does not change the numerical value of the total result

\[
MW^{LEP} = 80.412 \pm 0.042 \text{ GeV.} \tag{7.10}
\]

Figure 7.1 shows the results graphically. The L3 measurement result described in this thesis is somewhat lower than the alternative L3 result but consistent. The complementary L3 results were analysed in 2001 using the KORALW baseline Monte Carlo, whereas the analysis in this thesis is performed with the KandY Monte Carlo, which includes \( O(\alpha) \) corrections in DPA approximation for the four fermion final state.

The W mass is also directly measured by the CDF [72] and D0 [73] experiments at the Tevatron. The combined result is [74]

\[
MW^{Tevatron} = 80.452 \pm 0.059 \text{ GeV.} \tag{7.11}
\]

The direct measurements from LEP and Tevatron can be averaged which leads to the world average of:

\[
MW^{Average} = 80.425 \pm 0.034 \text{ GeV.} \tag{7.12}
\]

In the Standard Model framework parameters can be determined indirectly via Standard Model relations. The W mass can be derived from a Standard Model fit to electroweak observables to match the experimental data. Using the input parameters measured at LEP1 and SLD yields:

\[
MW^{LEP1+SLD} = 80.373 \pm 0.033 \text{ GeV.} \tag{7.13}
\]
If the top mass, $m_t$, measurements at CDF and D0 are added the result is

$$M_{W}^{LEP1+SLD+mt} = 80.386 \pm 0.023 \text{ GeV}. \quad (7.14)$$

Another indirect measurement is done at the NuTeV experiment. In the neutrino-nucleon scattering experiment the electroweak mixing angle $\sin^2 \theta_W$ is derived. From this the indirect mass is

$$M_{W}^{NuTeV} = 80.136 \pm 0.084 \text{ GeV}. \quad (7.15)$$

Measurements done at LEP and Tevatron agree well with each other. The indirect measurements from the electroweak data is also in good agreement with the combination of the direct measurement. However, the result obtained in the NuTeV experiment deviates at the level of 2.9$\sigma$ from the indirect measurements. There is no systematic effect found that may explain the difference.

Figure 7.2 [74] gives a graphical summary of the presented combined values for the W mass measurements. The upper part of the plot shows the direct measurements whereas the lower part of the plot shows the results obtained from the indirect measurement.

### 7.3 Width comparison

The W decay width is also measured at LEP by the other collaborations. Table 7.3 shows the results together with the LEP combination.

<table>
<thead>
<tr>
<th>experiment</th>
<th>$\Gamma_W$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>$2.13 \pm 0.14$</td>
</tr>
<tr>
<td>DELPHI</td>
<td>$2.11 \pm 0.12$</td>
</tr>
<tr>
<td>L3</td>
<td>$2.24 \pm 0.19$</td>
</tr>
<tr>
<td>OPAL</td>
<td>$2.04 \pm 0.18$</td>
</tr>
<tr>
<td>combined</td>
<td>$2.15 \pm 0.091$</td>
</tr>
</tbody>
</table>

Figure 7.3 shows the agreement between the result from this thesis with the other four results found at LEP.

Direct measurements of $\Gamma_W$ are also performed at CDF and D0. The Tevatron combination from these two experiments yields

$$\Gamma_{W}^{Tevatron} = 2.102 \pm 0.106 \text{ GeV}. \quad (7.16)$$

Figure 7.4 shows the comparison between the LEP and Tevatron determination. The average of these two measurements is

$$\Gamma_{W}^{Average} = 2.133 \pm 0.069 \text{ GeV}. \quad (7.17)$$
7.3. Width comparison

Figure 7.1: The mass $M_W$ per LEP experiment is represented for the $qql\nu$, the $qqqq$ channel and their combination. The combination includes the measurement from the threshold cross section. The LEP combination contains the alternative L3 result.
### 7.3. Width comparison

#### Conclusion and outlook

<table>
<thead>
<tr>
<th></th>
<th>W-Boson Mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TEVATRON</strong></td>
<td>80.452 ± 0.059</td>
</tr>
<tr>
<td><strong>LEP2</strong></td>
<td>80.412 ± 0.042</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>80.425 ± 0.034</td>
</tr>
<tr>
<td><strong>NuTeV</strong></td>
<td>80.136 ± 0.084</td>
</tr>
<tr>
<td><strong>LEP1/SLD</strong></td>
<td>80.373 ± 0.033</td>
</tr>
<tr>
<td><strong>LEP1/SLD/m_t</strong></td>
<td>80.386 ± 0.023</td>
</tr>
</tbody>
</table>

$X^2_{	ext{DoF}}$: 0.37/1

**Figure 7.2:** The upper part shows the direct measurements results obtained at LEP and Tevatron. The world average comes from the direct measurements. The indirect measurement is indicated by the triangular point in the graph. Also the NuTeV results, which deviate 2.9$\sigma$ from the indirect measurement, is shown.

**Figure 7.3:** Values found for the width of the W boson at all the four experiments at LEP are given individually. The LEP combination includes the alternative L3 result. All the measurements are consistent.
Just as for the mass of the W, $\Gamma_W$ can also be determined indirectly from the Standard Model framework parameters measured at LEP1, SLD and Tevatron. A summary is shown in figure 7.4.

**W-Boson Width [GeV]**

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Gamma_W$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEVATRON</td>
<td>$2.102 \pm 0.106$</td>
</tr>
<tr>
<td>LEP2</td>
<td>$2.150 \pm 0.091$</td>
</tr>
<tr>
<td>Average</td>
<td>$2.133 \pm 0.069$</td>
</tr>
<tr>
<td>$p\bar{p}$ Indirect</td>
<td>$2.141 \pm 0.057$</td>
</tr>
<tr>
<td>LEP1/SLD</td>
<td>$2.092 \pm 0.003$</td>
</tr>
<tr>
<td>LEP1/SLD/$m_t$</td>
<td>$2.092 \pm 0.002$</td>
</tr>
</tbody>
</table>

**Figure 7.4:** The world average of the W boson width is derived from direct measurements of LEP and Tevatron. Indirect electroweak determinations are shown for comparison.

### 7.4 Constraint on the Higgs mass

From the electroweak measurements constraints on the mass of the Higgs boson can be inferred. In section 7.2 the result for the indirect measurement from LEP1 and SLD of $M_W$ is given in equation (7.13). The 68% contour level of the indirect measurements of the W mass and top mass are shown in figure 7.5 [74] as a solid curve. The relation between the W, top and Higgs mass is indicated by the diagonal solid line with the Standard Model prediction of the Higgs mass between 114 and 1000 GeV. As can be seen in figure 7.5 the indirect and direct measurement overlap and prefer a low value of the Higgs mass.

The Standard Model fit provides a constraint on the Higgs mass. The result for the Higgs mass of the fit when all data from LEP, SLD, CDF and D0 is used, corresponds to the minimum of the solid curve in figure 7.6 [74]. This minimum and its one sigma deviation is found at

$$M_H = 113^{+62}_{-42} \text{GeV},$$

(7.18)

with non-Gaussian errors considering the Higgs mass enters logarithmically in the fit. The dark grey band around the solid curve takes into account the estimated theoretical uncertainties, due to missing higher order corrections.

The dotted curve shows the variation if the NuTeV results are also considered in the analysis.

From negative results of direct searches of the Higgs boson it follows that the lower limit on $M_H$ is approximately 114 GeV. In figure 7.6 the exclusion region by the direct searches is represented by the grey band. The upper limit on the mass $M_H$ with 95% confidence level, including
7.5. Future colliders

The next generation of colliders to probe deeper into the structure of matter will comprise two complementary types of colliders.

The first type of collider is a circular hadron collider which is currently under construction at CERN, the Large Hadron Collider (LHC). Its very high mass reach and high luminosity will allow possible new physics processes to be covered. High-statistics samples will be used to calibrate the detector and study the standard physics.

The second type of collider is an $e^+e^-$ Linear Collider (LC). New particles can be directly produced and studied in detail. Its precision measurements will allow sensitivity to new phenomena.

Figure 7.5: The comparison between indirect (LEP1 and SLD) and direct (LEP2 and Tevatron) measurements of the W mass and top quark. The solid contour represents the indirect measurements at 68% CL, while the dotted contour is the 68% CL from the direct measurement. The band shows the Standard Model prediction for the masses for various values of $M_H$.

Experimental and theoretical uncertainty is 237 GeV. This constrains the search window to look for the Higgs boson.

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The second type of collider is an $e^+e^-$ Linear Collider (LC). New particles can be directly produced and studied in detail. Its precision measurements will allow sensitivity to new phenomena.
Figure 7.6: The $\chi^2$ of the Standard Model fit as a function of the Higgs mass. The minimum corresponds to the preferred value of the Higgs mass. The band represents the theoretical uncertainty. Direct searches have excluded the lower values in the shaded band. Inclusion of the NuTeV result is represented by the dotted curve.

far above the centre-of-mass scale.

### 7.5.1 Large Hadron Collider

The Large Hadron Collider (LHC) will be operational in 2007. At this accelerator two proton-beams will be collided head-on at a centre-of-mass energy of 14 TeV.

The W boson will be produced by $q\bar{q}$ annihilation.

\[
pp \rightarrow W + X \quad (7.19)
\]
\[
W \rightarrow l\nu_l. \quad (7.20)
\]

with $l = e, \mu$, for which the cross section is about 30 nb. Since the boost of the centre-of-mass energy along the beam axis is difficult to determine the longitudinal component of the neutrino
cannot be measured. Due to this the transverse mass $M_T^W$ is calculated from the transverse momenta of the charged lepton and the neutrino

$$M_T^W = \sqrt{2p_T^l p_T^\nu (1 - \cos \Delta \phi)},$$

(7.21)

where $l = e, \mu$ and $\Delta \phi$ the azimuthal separation between the two leptons. The transverse momentum of the neutrino is obtained from the measured $p_T^l$ and the transverse momentum $\bar{u}$ of the system recoiling against the W.

Figure 7.7 [75] shows the $M_T^W$ mass spectrum. The mass could be extracted by a maximum likelihood fit to the data with a Monte Carlo probability density distribution. The distribution is smeared out by several effects. This is in particular true for the trailing edge which reduces the sensitivity to the mass. One single bunch crossing may produce multiple interactions, these pile-up events significantly smear the transverse mass. Therefore, the mass measurement is best performed at low luminosity.

LHC will run in the first year with a luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$. This will provide an inte-
grated luminosity of the order of $10 \text{ fb}^{-1}$. After the initial phase the instantaneous luminosity will be increased to $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ collecting an integrated luminosity of about $100 \text{ fb}^{-1}$ a year.

In the first year of LHC running the estimated statistical uncertainty on $M_W$ will be smaller than $2 \text{ MeV}$. The dominant part in the error of the mass will come from the systematic uncertainties. The precision of the measurement will be affected by the physics knowledge and detector knowledge. As an illustration table 7.4 [75] shows an estimation of some of the uncertainties at the ATLAS detector.

Table 7.4: In the first year of LHC running ATLAS is expected to collect a integrated luminosity of $10 \text{ fb}^{-1}$. The estimated uncertainty for each lepton family is shown in the table.

<table>
<thead>
<tr>
<th>source</th>
<th>$\Delta M_W \text{ [MeV]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistics</td>
<td>$&lt; 2$</td>
</tr>
<tr>
<td>detector performance</td>
<td></td>
</tr>
<tr>
<td>energy and momentum scale</td>
<td>15</td>
</tr>
<tr>
<td>energy resolution</td>
<td>5</td>
</tr>
<tr>
<td>lepton identification</td>
<td>5</td>
</tr>
<tr>
<td>recoil model</td>
<td>5</td>
</tr>
<tr>
<td>physics knowledge</td>
<td></td>
</tr>
<tr>
<td>recoil model</td>
<td>5</td>
</tr>
<tr>
<td>$W$ width</td>
<td>7</td>
</tr>
<tr>
<td>Parton distribution function</td>
<td>10</td>
</tr>
<tr>
<td>radiative decays</td>
<td>$&lt; 10$</td>
</tr>
<tr>
<td>$p_T^W$</td>
<td>5</td>
</tr>
<tr>
<td>background</td>
<td>5</td>
</tr>
<tr>
<td>total</td>
<td>25</td>
</tr>
</tbody>
</table>

The total estimated error for ATLAS and CMS separately is in the order of $25 \text{ MeV}$. Combining both measurements could lead to a precision better than $15 \text{ MeV}$ for $M_W$.

7.5.2 Linear Collider

Another type of collider which is under study is a high-energy high-luminosity electron-positron linear collider (LC). This type of collider could reach a centre-of-mass energy of $500 \text{ GeV}$ with
about 500 fb\(^{-1}\) within five years, if a design luminosity of approximately \(2 \times 10^{34}\) cm\(^{-2}\)s\(^{-1}\) is realised.

Although the mass reach of a LC is less than the LHC, it is sensitive to per mill level deviations from the Standard Model, due to its cleaner environment. Such sensitivity corresponds to probing new physics at energy scales as high as 10 TeV [76].

Such a high-luminosity linear collider will pose an opportunity to measure \(M_W\) with a high accuracy. This is best measured with a dedicated run at the threshold of the WW production [77]. The threshold scan requires an accurate calculation of the cross-section dependence on \(M_W\).

The strategy is aimed to look at the WW cross section near threshold where the \(t\)-channel electron neutrino exchange process dominates. As in this channel the WW only couples to the \(e^+e^-\) helicity combination, beam polarisation states allow enhancement or suppression of the signal. With a five point scan \(160.4 < \sqrt{s} < 162\) GeV and a point at \(\sqrt{s} = 170\) GeV and if a polarisation of 60\% can be achieved a precision of 6 MeV can be attained.

### 7.6 Muon lifetime

The Standard Model requires 24 parameters in the electroweak sector from experimental measurements. These parameters are six quark masses, six lepton masses, four CKM quark mixing angles and phases, four lepton mixing angles and phases and a set of four other electroweak parameters to be chosen from the set \{\{\alpha, M_Z, M_W, M_H\}, {\alpha, M_Z, \sin \theta_W, M_H}, {\alpha, M_Z, G_F, M_H}\}. Equation (1.47) gives the interdependence between the \(M_W\) on one side and \(\alpha\) and the Fermi constant \(G_F\) on the other side. Their values along with their absolute and relative errors are [78]:

\[
\begin{align*}
\alpha &= 1/137.03599911(46) \quad (0.0034\ \text{ppm}); \\
M_Z &= 91.1876(21) \ \text{GeV} \quad (23\ \text{ppm}); \\
G_F &= 1.16637(1) \times 10^{-5} \ \text{GeV}^{-2} \quad (9\ \text{ppm}).
\end{align*}
\]

Accurate precision is achieved for the electroweak parameters \(M_Z\) and \(\alpha\) in experiments. The uncertainty on \(G_F\) can also be improved.

The Fermi constant \(G_F\) is directly associated with the muon life time [79]

\[
\tau^{-1} = \frac{G_F^2 m_\mu^5}{192\pi} (1 + \Delta q),
\]

with \(\Delta q\) including higher order QED and QCD corrections calculated in the theory. The theoretical uncertainty is reduced and an experimental result in the order of 0.5 ppm is becoming feasible with respect to the theoretical limit.

The uncertainty on measurement of \(G_F\) exists of the following experimental contributions [80]:

\[
\frac{\Delta G_F}{G_F} = \sqrt{(\frac{5}{2} \frac{\Delta m_\mu}{m_\mu})^2 + \left(\frac{1}{2} \frac{\Delta \tau_\mu}{\tau_\mu}\right)^2 + \left(\frac{4 m_\nu_e}{m_\mu^2}\right)^2} = \sqrt{0.38^2 + 9^2 + [10^2/0.3]^2} \ \text{ppm.}
\] (7.23)

The \(m_\nu_e\) is assumed to be non-zero. With the upper bound of \(m_\nu_e \leq 170\ \text{keV}\) the relative shift on \(G_F\) is 10 ppm. With the expected reduced upper bound at 30 \text{keV} the uncertainty on \(G_F\) becomes
in the order of 0.3 ppm The main contribution to the uncertainty in $G_F$ arises from the muon lifetime $\tau_\mu$ measurement.

The Muon Lifetime ANalysis ($\mu$Lan) experiment at Paul Scherrer Institute (PSI) is an experiment which aims to measure the positive muon lifetime to 1 ppm precision, thus the Fermi coupling constant to 0.5 ppm [81].

The $\mu$Lan detector records the decay of approximately 20 muons, which are brought to rest in a target during an accumulation period. The decays are recorded during about 10 muon lifetimes (22 $\mu$s). A cycle is repeated until more than $10^{12}$ decays are recorded.

It is expected to do a full production run at the beginning of summer in 2005 with a fully working experiment.

### 7.7 Conclusion

This thesis describes the measurement of the mass and width of the $W$ boson. Data recorded with the L3 detector is analysed for centre-of-mass energies between 189 and 208 GeV taken in the period from 1998 until 2000. This corresponds with a total integrated luminosity of 629.3 pb$^{-1}$. The invariant mass spectrum of the semi-leptonic and fully hadron decay channels of the $W$ are analysed. The results of these measurements are:

\[
M_W = 80.323 \pm 0.069 \text{ GeV}, \quad (7.24)
\]
\[
\Gamma_W = 2.27 \pm 0.14 \text{ GeV}. \quad (7.25)
\]

Direct measurements at LEP and Tevatron gives a world average of:

\[
M_W^{\text{Average}} = 80.425 \pm 0.034 \text{ GeV}. \quad (7.26)
\]
\[
\Gamma_W^{\text{Average}} = 2.133 \pm 0.069 \text{ GeV}. \quad (7.27)
\]

The next generation of colliders will significantly improve the uncertainty on the mass of the $W$. It is expected that the uncertainty on $M_W$ will be better than 15 GeV for the measurement at LHC. This will be even surpassed by the experiments done at linear collider, which will improve the uncertainty by about a factor of 2 less compared to LHC, resulting in an uncertainty in the order of 6 MeV.
7.7. Conclusion