54. Mass and Width of the W Boson

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Precision determination of the W mass is of great importance in testing the internal consistency of the Standard Model. From the time of its discovery in 1983, the W boson has been studied and its mass determined in $p\bar{p}$ and e^+e^- interactions; it is currently studied in pp interactions at the LHC. The mass and width definition used here corresponds to a Breit-Wigner with mass-dependent width.

Production of on-shell W bosons at hadron colliders is tagged by the high p_{T} charged lepton from its leptonic decay modes. Owing to the unknown parton-parton effective energy and missing energy in the longitudinal direction, the hadron collider experiments reconstruct the transverse mass of the W boson, and derive the W mass from comparing the transverse mass distribution with Monte Carlo predictions as a function of the mass m_W. The transverse momentum of the charged lepton itself and the transverse missing energy (arising from the neutrino in W decay) are also sensitive to the W mass and used in its determination. These analyses use the electron and muon decay modes of the W boson.

At the e^+e^- collider LEP, a precise knowledge of the beam energy enables one to determine the $e^+e^- \to W^+W^-$ cross section as a function of center of mass energy, as well as to reconstruct the W mass precisely from its decay products, even if one of them decays leptonically. Close to the W^+W^- production threshold ($\sqrt{s} = 161\,\mathrm{GeV}$), the dependence of the W-pair production cross section on m_W is large, and this was used to determine m_W. At higher centre-of-mass energies (172 to 209 GeV) this dependence is much weaker, thus W bosons were directly reconstructed and the mass determined as the invariant mass of the decay products, improving the resolution with a kinematic fit.

In order to compute the LEP average W mass, each experiment provided its measured W mass for the $q\bar{q}q\bar{q}$ and $q\bar{q}\ell\nu$, $\ell = e, \mu, \tau$ channels at each center-of-mass energy, along with a detailed break-up of uncertainty contributions: statistical, uncorrelated, partially correlated and fully correlated systematics [1]. These results have been combined to obtain a LEP average W mass of $m_W = 80.376 \pm 0.033\,\mathrm{GeV}$. Errors on m_W due to uncertainties in the LEP beam energy (9 MeV), and possible effect of color reconnection (CR) and Bose-Einstein correlations (BEC) between quarks from different W bosons (8 MeV) are included. The mass difference between $q\bar{q}q\bar{q}$ and $q\bar{q}\ell\nu$ final states (due to possible CR and BEC effects) is $-12 \pm 45\,\mathrm{MeV}$. In a similar manner, the results on the total width of the W boson obtained at LEP have been combined, resulting in an average of $\Gamma_W = 2.195 \pm 0.083\,\mathrm{GeV}$ [1].

The two Tevatron experiments CDF and D0 have also identified common systematic errors. Between the two experiments, uncertainties due to the parton distribution functions (PDF), radiative corrections, and choice of mass (width) in the width (mass) measurements are treated as correlated. An average W width of $\Gamma_W = 2.046 \pm 0.049$ GeV [2] is obtained. Errors of 20 MeV and 7 MeV accounting for PDF and radiative correction uncertainties in this width combination dominate the correlated uncertainties. The CDF and D0 measurements of $80.387 \pm 0.019\,\mathrm{GeV}$ [3] and $80.375 \pm 0.023\,\mathrm{GeV}$ [4], respectively, obtained with Run-II data, are the two single most precise determinations of the W boson mass at the Tevatron. Combining the results from Run-I and Run-II of the Tevatron using an improved treatment of correlations, following the procedure used in [5], the results are $80.389 \pm 0.019\,\mathrm{GeV}$ for CDF and $80.383 \pm 0.023\,\mathrm{GeV}$ for D0. A combination of all pre-2022 CDF and D0 results yields a Tevatron average of $80.387 \pm 0.016\,\mathrm{GeV}$ [5], with common uncertainties of 10 MeV (PDF) and 4 MeV (radiative corrections).

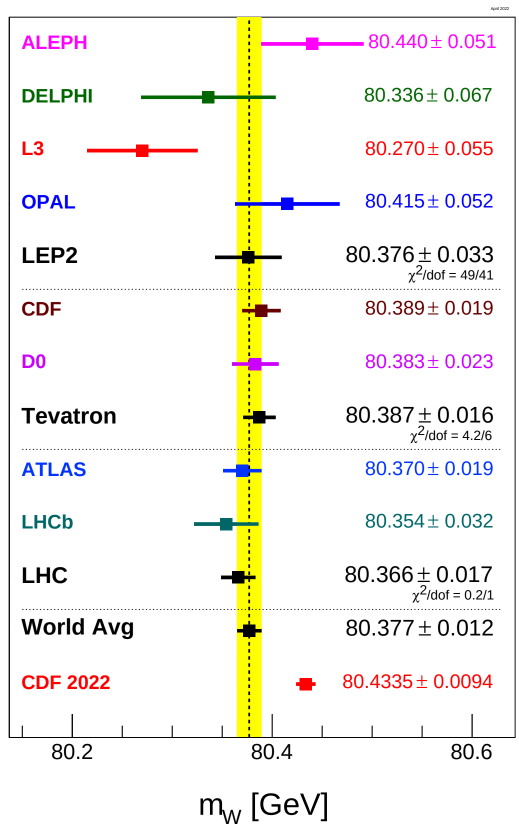

Figure 54.1: Measurements of the W boson mass by the LEP, Tevatron and LHC experiments. The pre-2022 CDF result, used in the world average, is superseded by the new CDF 2022 result.

Using pp collisions at $\sqrt{s} = 7$ TeV, the ATLAS collaboration has published the first measurement of the W boson mass at the LHC, $m_W = 80.370 \pm 0.019$ GeV [6], which is of similar precision as the best measurements of CDF and D0. The LHCb collaboration has measured the W boson mass in pp collisions at $\sqrt{s} = 13$ TeV at the LHC, $m_W = 80.354 \pm 0.032$ GeV [7]. Combining the results from ATLAS and LHCb using the BLUE procedure [8, 9] assuming a correlated uncertainty of 9 MeV (PDF), the LHC average is $m_W = 80.366 \pm 0.017$ GeV.

The results obtained by the experiments at the different accelerators are all in good agreement with each other. Assuming a correlated uncertainty of 7 MeV, a hadron collider average of the Tevatron and LHC measurements of $m_W = 80.377 \pm 0.013$ GeV is obtained, and a world average of $m_W = 80.377 \pm 0.012$ GeV, combining with the LEP result assuming no correlation, again using the BLUE procedure for these averages.

The LEP, Tevatron and LHC results on mass and width are compared in Fig. 54.1 and Fig. 54.2. The Standard Model prediction from the electroweak fit, including Z-pole data and the measured masses of the top quark and of the Higgs boson, gives a W-boson mass of $m_W = 80.356 \pm 0.006$ GeV (see Section 10, Electroweak Model and Contraints on New Physics, J.Erler and A.Freitas, 2022, this review) and a W-boson width of $\Gamma_W = 2.091 \pm 0.001$ GeV [10], which are in good agreement with the measurements.

In April 2022, after the cut-off of results for this review, the CDF collaboration published a

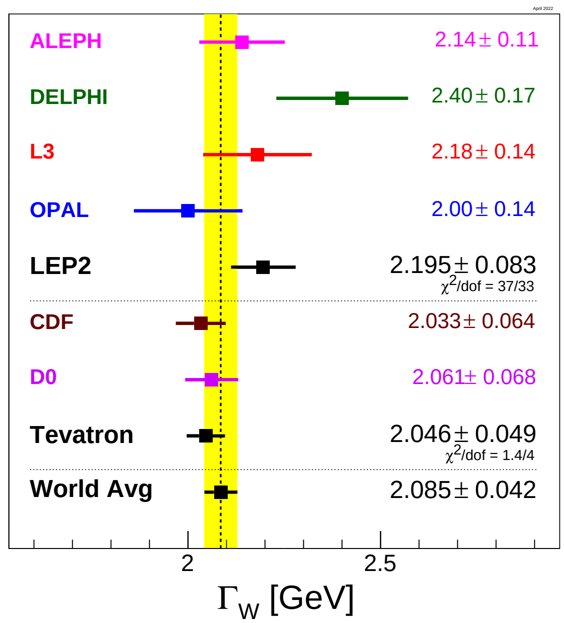

Figure 54.2: Measurements of the W-boson width by the LEP and Tevatron experiments.

measurement of the W mass based on their full Run-II dataset of $8.8\,\mathrm{fb}^{-1}$, with much reduced uncertainty: $80,433.5 \pm 9.4$ MeV [11][1]. This new CDF Run-II result is of higher precision than our world average of $80.377 \pm 0.012\,\mathrm{GeV}$. However, the two determinations disagree significantly, as visible in Fig. 54.1. A probability ideogram comparing the results from Fig. 54.1 is shown in Fig. 54.3 (see Section 5.2 in the Introduction of this review on the construction of ideograms).

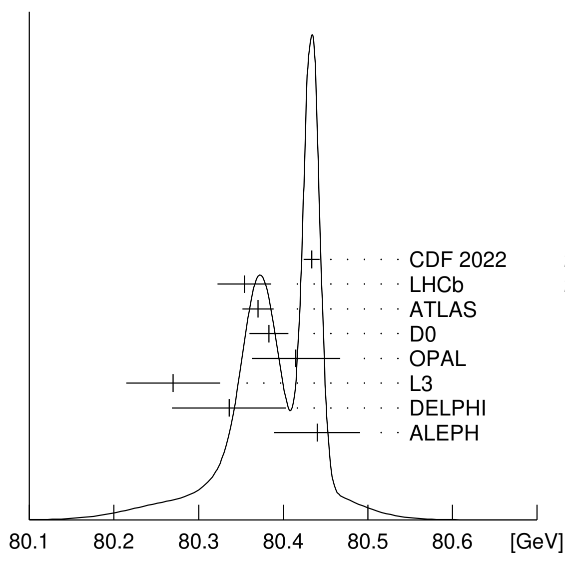

Figure 54.3: Ideogram showing the compatibility of all W-boson mass measurements, replacing the pre-2022 CDF result by the new CDF 2022 result.

[1] The new result includes the $2.2\,\mathrm{fb}^{-1}$ of data used for the previous CDF Run-II result of $80.387 \pm 0.019\,\mathrm{GeV}$ [3]. Incorporating the improved understanding of PDFs and track reconstruction, the central value of the $2.2\,\mathrm{fb}^{-1}$ result is increased by 13.5 MeV to 80,400.5 MeV [11].

For calculating a new world average, replacing the old CDF Run-II result [3] by the new one [11], the uncertainties of all results need to be scaled by a factor of about two in order to achieve a χ^2 per degree of freedom of unity (see Section 5.2 in the Introduction of this review on the definition of the scale factor). The world average quoted above (80.377 ± 0.012 GeV) increases significantly in central value, by up to 40 MeV, while its scaled uncertainty increases by up to 6 MeV, with the exact changes depending on the assumptions made concerning correlated uncertainties. A detailed understanding of the results and their correlations is needed. Corresponding studies are currently being undertaken by the experiments.

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