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 $p\bar{p}$, e^+e^- and pp interactions. The mass m_W and width Γ_W definition used in measurements corresponds to a Breit-Wigner with mass-dependent width with a propagator $\propto 1/(s - m_W^2 + is\Gamma_W/m_W)$.

At the e^+e^- collider LEP, the dependence of the W-pair production cross section on m_W is large close to the production threshold ($\sqrt{s} \approx 2m_W \approx 161\,\mathrm{GeV}$). Hence this was used for the mass measurement, together with the precise knowledge of the beam energy. At higher center-of-mass energies ($\sqrt{s} = 172$ to $209\,\mathrm{GeV}$) 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. The LEP average W mass was then determined in a combination of the measurements from each experiment for all channels ($q\bar{q}q\bar{q}$ and $q\bar{q}\ell\nu,\ \ell = e, \mu, \tau$) and centre-of-mass energies along with a detailed decomposition of uncertainty contributions [1]. This yielded a combined 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.

Currently the most precise measurements of the W mass are performed in hadron collisions at the Tevatron ($p\bar{p}$) and the LHC (pp). These analyses use the electron or muon decay modes of the W boson ($\ell\nu,\ \ell = e, \mu$) and tag the production of W bosons with the high p_T charged lepton and missing energy transverse to the beam direction arising from the neutrino. Owing to the unknown parton-parton effective energy and the unmeasured 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 distribution with Monte Carlo predictions obtained for different values of m_W. The transverse momentum of the charged lepton itself and the transverse missing energy are also sensitive to the W mass and used in its determination. Specifically, measurements by the LHC experiments so far rely primarily on the charged lepton p_T distribution.

In the past, the two Tevatron experiments CDF [2] and D0 [3] provided a combined value for the W mass by identifying common systematic uncertainties due to the parton distribution functions (PDF), radiative corrections, and choice of the width [4]. With the first mass results from the two LHC experiments, ATLAS [5] and LHCb [6], a simplified W-mass average for the LHC was obtained, assuming a correlated uncertainty of 9 MeV (PDF) [7]. Similarly, assuming a correlated uncertainty of 7 MeV, a hadron collider average of the Tevatron and LHC measurements was obtained [7].

All measurements were in good agreement with each other, until the CDF collaboration published a result $m_W = 80.4335 \pm 0.0094\,\mathrm{GeV}$ [8] in April 2022, based upon their full Run-II dataset of $8.8\,\mathrm{fb}^{-1}$. This newer result is of higher precision than the 2022 world average, but the two values disagree significantly.[1] The LHC-TeV W-mass Working Group with W-mass experts from all hadron collider experiments, CDF, D0, ATLAS, CMS, LHCb, has been working to understand better the nature of this disagreement and suggest a new world average value of the W mass. Theoretical corrections, uncertainties and their correlations between different hadron collider experiments have

[1]The 2022 CDF result includes the $2.2\,\mathrm{fb}^{-1}$ of data used for the previous CDF Run-II result of $80.387 \pm 0.019\,\mathrm{GeV}$ [2]. Incorporating the improved understanding of PDFs and track reconstruction , the central value of the $2.2\,\mathrm{fb}^{-1}$ result is increased by $0.0135\,\mathrm{GeV}$ to $80.4005\,\mathrm{GeV}$ [8].

been evaluated in detail and used in the combination: the central values are corrected to a common theory description and PDF set, and the uncertainties and correlations due to PDFs have been re-evaluated. The group reported in 2023 [9] that a combination of all W-mass measurements has a probability of compatibility of only 0.5%, and is therefore disfavoured. A 91% probability of compatibility is obtained when the CDF Run-II measurement is removed. The corresponding value of the W boson mass is $m_W = 80369.2 \pm 13.3$ MeV, which we currently quote as the World Average. The results on the W mass published by the experiments are shown in Figure 54.1.

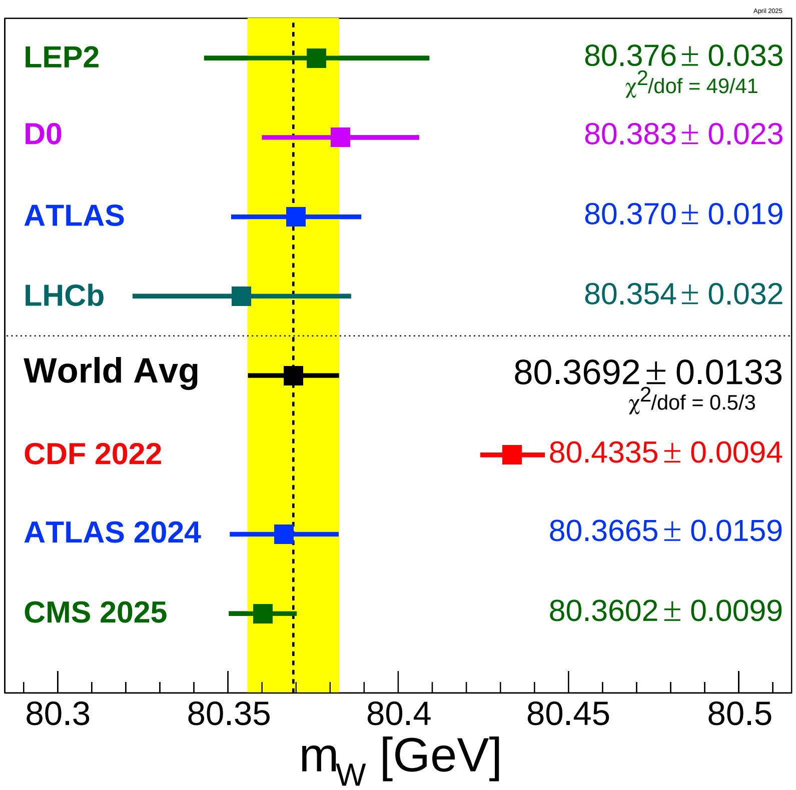

Figure 54.1: Measurements of the W-boson mass by the LEP, Tevatron and LHC experiments as well as their combination. Below the combination, three further measurements are shown that are currently not used in the world average: the CDF 2022 result, the ATLAS 2024 result that supersedes their previous measurement, and the first result by the CMS Collaboration submitted for publication in December 2024.

Two new results have appeared since this combination. The ATLAS Collaboration published a refined analysis of their data used in [5] and obtained a more precise mass value of 80.3665 ± 0.0159 GeV [10]. The CMS Collaboration submitted for publication their first measurement, reaching a precision close to the CDF Run-II result of $m_W = 80.3602 \pm 0.0099$ GeV [11]. While these measurements are close to the value currently quoted as the World Average [9], a detailed combination by the LHC-TeV W-mass Working Group is still ongoing.

Similarly, the W boson total width has been measured in e^+e^-, $p\bar{p}$ and pp collision data. The combined LEP average of the W boson total width was determined to be $\Gamma_W = 2.195 \pm 0.083$ GeV [1], with a good internal consistency of 27% χ^2 probability. The most recent width measurements from the Tevatron experiments CDF and D0 were combined to $\Gamma_W = 2.046 \pm 0.049$ GeV [12], also with very good internal compatibility of 84%. The latest and most precise measurement to date was performed by ATLAS yielding $\Gamma_W = 2.202 \pm 0.047\,\mathrm{GeV}$ [10]. All results are shown in Figure 54.2 together with our weighted average of the three results of $\Gamma_W = 2.14 \pm 0.05\,\mathrm{GeV}$, where the error is scaled by a factor of 1.7 to account for a tension between the three width results (5.3% χ^2 probability) as shown in Figure 54.2.

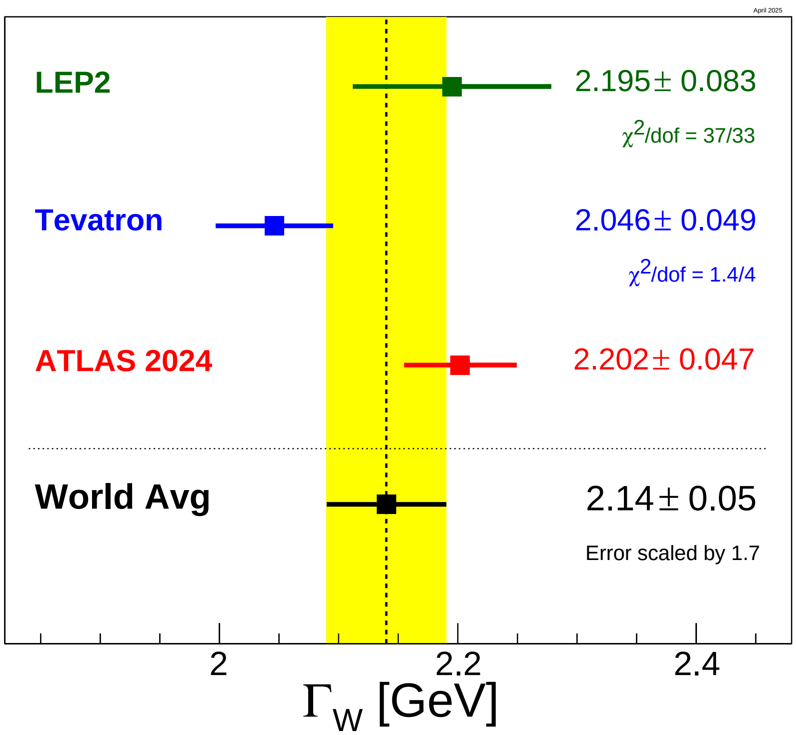

Figure 54.2: Measurements of the W-boson width by the LEP, Tevatron and LHC experiments.

The Standard Model prediction from an electroweak fit, including Z-pole data and the measured masses of the top quark and of the Higgs boson but excluding results on m_W and Γ_W, implies a W-boson mass of $m_W = 80.353 \pm 0.006\,\mathrm{GeV}$ and a W-boson width of $\Gamma_W = 2.089 \pm 0.001\,\mathrm{GeV}$; see Section 10, Electroweak Model and Constraints on New Physics, J.Erler and A.Freitas, 2024, this review. Note that the electroweak fit of Section 10 to all measurements uses slightly different measurements of the W boson mass and width as explained there.

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