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The discovery of the W and Z bosons in 1983 was certainly one of the groundbreaking moments in particle physics, confirming key predictions of the electroweak theory. The experimental signatures of these particles, as mediators of the weak force, were recorded for the first time by UA1 and UA2 experiments, led by Carlo Rubbia and Pierre Darriulat, respectively. Both particle detectors measured protons and antiprotons collisions at the Super Proton Synchrotron (SPS). Apart from the high collision energies at the SPS, the development of the "stochastic cooling" technique by Simon Van der Meer was crucial to significantly increase the number of particle collisions to produce a sufficiently large number of W and Z bosons to be experimentally confirmed. Their pivotal contributions to the confirmation of the existence of these particles, earned both Rubbia and Van der Meer the Nobel Prize in Physics in 1984. Along with the discovery, a first estimate of the W and Z boson masses has been published.

In the year 2022, a new measurement of the W boson mass made headlines worldwide due to its deviation by more than seven standard deviations from the prediction of the Standard Model of particle physics. To understand this measurement and its interpretation correctly, one must first recall the unified electroweak theory, formulated as early as the 1960s by S. Glashow, S. Weinberg, and A. Salam. This theory uses only a few parameters — namely, the masses of the W boson (m_W) and Z boson (m_Z), the fine structure constant (α_{em}), the Fermi constant (G_F), and the electroweak mixing angle ($\sin^2\theta_W$) — to represent the entire theory of electromagnetic and weak interactions.

What is particularly remarkable here is that after the unification of electric and magnetic phenomena by Maxwell in the 19th century, this marked the second instance in physics history where two natural forces could be described by a unified theoretical framework. The five parameters mentioned in the electroweak theory are related through two equations. For example, the electroweak mixing angle can be expressed in terms of the masses of the W and Z bosons. Since the unified electroweak theory is a quantum field theory, quantum corrections, generally referred to as loop corrections, must be taken into account in these relationships. Therefore, the W boson mass depends not only directly on the Z boson mass and the electroweak mixing angle but also indirectly on the Higgs boson mass and the top quark mass.

Examples of loop corrections that directly affect the measured W boson mass are schematically illustrated in Figure 1. These relationships can be mathematically determined with high precision, allowing the known relationships of the W boson mass, the Z boson mass, the electroweak mixing angle, and the top quark mass, along with their corresponding measurements, to determine the mass the Higgs boson must have to match the observed measurements with theoretical predictions. Indeed, this approach was already used in the 1990s, indicating the range within which the Higgs boson mass would be expected before its discovery. Following the discovery of the Higgs boson and the first measurement of its mass, all parameters necessary for a full description of the electroweak sector were known.

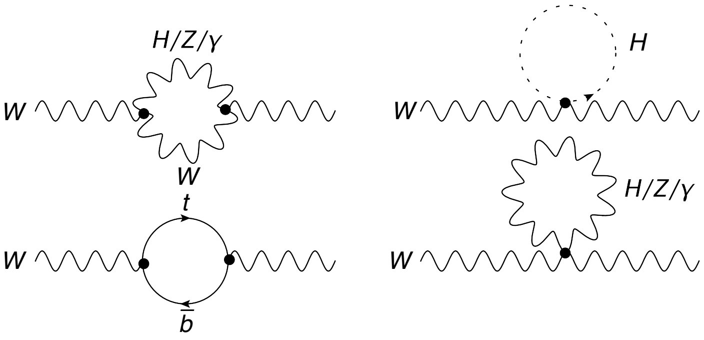

Figure 1: Illustrations of Quantum Corrections to the W Boson in the Standard Model using Feynman Diagrams.

The special interest in the W boson mass can now be explained by the fact that all Standard Model particles interact with the W boson since they all carry a weak charge. If we assume that new, as-yet-undiscovered particles can also interact with the W boson, these particles would also appear in quantum mechanical loop corrections and could imply a discrepancy between the predicted W boson mass in the Standard Model and the actual measured mass. One of the most popular models beyond the Standard Model is supersymmetry, and these particles would lead to additional quantum mechanical corrections that predict a higher W boson mass. A second important aspect is that the relative theoretical uncertainty on the predicted W boson mass, at 0.007 %, is significantly smaller than the previous relative experimental accuracy of 0.016 % in 2012, the year of the Higgs boson discovery. Since a discrepancy was observed between the measured value of 80385 ± 15 MeV/c^2 and the predicted value of 80359 ± 11 MeV/c^2, it was up to experimental physicists to reduce measurement uncertainty to potentially gain insights into new physics.

The most precise measurements of the W boson mass have been conducted at hadron colliders such as the Large Hadron Collider (LHC) at CERN and the Tevatron at Fermilab. While the LHC collides protons at center-of-mass energies up to 13 TeV, the Tevatron investigates collisions of protons and antiprotons at a center-of-mass energy of 1.96 TeV. However, the fundamental concept for measuring the W boson mass is very similar at both accelerators. Due to the short-lived nature of the W boson, only its decay products can be detected. Although a W boson most commonly decays into a quark and an antiquark, this decay channel is not used for mass determination at a hadron collider. The quarks from a W boson decay will immediately hadronize, i.e., form a spray of stable particles in the direction of the original quark, which are reconstructed in the detector as particle jets. The problem, however, is that the vast majority of proton-proton or proton-antiproton collisions produce similar event signatures. As a result, W boson decays into two quarks cannot be distinguished with sufficiently high precision due to the enormous background processes. Instead, focus is placed on leptonic decay channels, especially the decay into an electron and an electron neutrino or into a muon and a muon neutrino. Determining the W boson mass is thus reduced to measuring the energy of its decay products.

The challenge here is that neutrinos cannot be directly detected; they only appear as missing (transverse) energy in the detector. One observable that can be measured and provides insight into the W boson mass is the (transverse) momentum of the muon resulting from the W boson decay. To understand the measurement concept, one must use perhaps the most famous equation in physics, $E = mc^2$, which denotes the equivalence of energy and mass. The mass of a W boson, approximately 80000 MeV/c^2, is transferred upon decay equally as kinetic energy and momentum to its decay products. A higher W boson mass, therefore, correlates with a higher expected muon momentum compared to a lower mass.

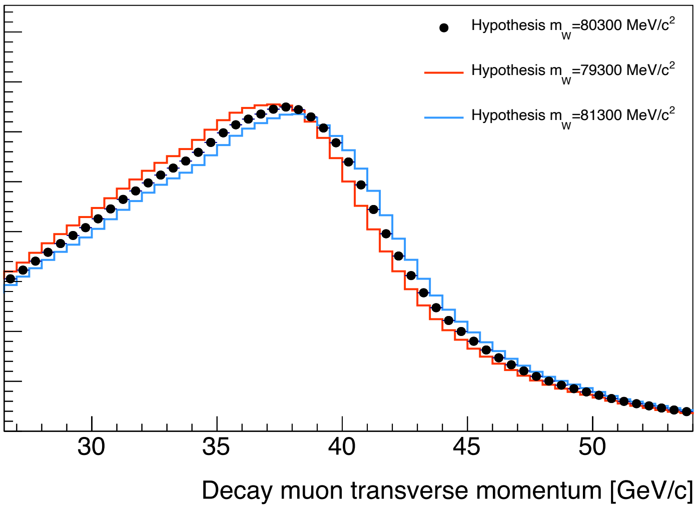

Figure 2: Expected transverse momentum distribution of muons, stemming from the decay of a W Boson for different hypothesis of the W boson mass.

Figure 2 illustrates the expected distribution of the measured transverse momentum of W boson decay muons for three different mass hypotheses. The continuous shape of the spectrum has two causes: first, only the momentum component in the transverse plane with respect to the beam-axis is shown, as this is the physical relevant observable in proton-proton collisions. Second, the W bosons are not created at rest, but have an initial momentum, which itself has a continuous spectrum that translates also to momentum to its decay leptons. Despite of these technical complications, the basic principle is simple: one simply needs to compare the observed distribution with different simulated hypotheses and determine the value that best describes the data.

Although the core measurement principle is straightforward, achieving the necessary precision is challenging. To reach experimental precision within a few per mille, two key aspects must be meticulously understood: first, the detector system must be calibrated with exceptional precision. This is typically done by studying known observables, such as the Z boson or J/Psi meson masses, whose properties are very well known. To illustrate the complexity and precision required in these measurements, even small detector deformations of a few hundred micrometers can introduce significant biases in the final results. Second, the production of W bosons in hadron collisions must be thoroughly understood. W bosons are not produced exactly at rest; they have a variable initial momentum that influences the energy of the decay products. This requires testing both perturbative and non-perturbative theoretical models, as well as estimating uncertainties due to limited knowledge of the proton's internal structure.

The complexity of such a measurement also explains the typical time to publication: the first W boson mass measurement at the LHC was published by the ATLAS collaboration in 2017, based on data collected in 2011. In April 2022, eleven years after the Tevatron accelerator was decommissioned, the CDF collaboration published its final measurement, reporting a result of $m_W = 80434 \pm 9$ MeV/c^2. This result is remarkable for two reasons: first, the uncertainty achieved was half that of previous single measurements. To understand the experimental rigor required for such accuracy, consider that an uncorrected shift in the track chambers of the particle detectors by fractions of a millimeter would shift the measured m_W value by many MeV/c^2. Even more intriguing is the significant deviation of seven standard deviations from the Standard Model's indirect prediction implied by the CDF measurement. Could this be the long-sought hint of new physics at particle accelerators?

Most particle physicists were cautious about drawing such conclusions after the result became public. Comparing the new measurement to previous results reveals a significant discrepancy. When combining past measurements from the LEP experiments with those from ATLAS and LHCb at the LHC, as well as the D0 experiment measurement at Fermilab, an approximate value of $m_W = 80369.2 \pm 13.3$ MeV/c^2 emerges. This value not only aligns well with the Standard Model prediction but also deviates by about four standard deviations from the new CDF experiment result. Since then,

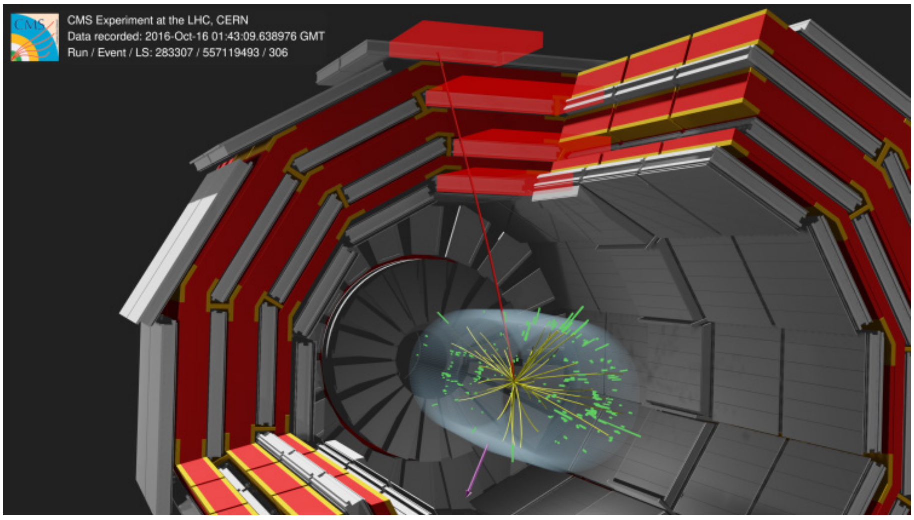

Figure 3: Event display of a reconstructed W boson candidate event in the muon decay channel by the CMS detector. The reconstructed muon is shown as red line, while the missing transverse energy in the event is indicated as purple line. Source: CMS Collaboration, CERN

the ATLAS collaboration has refined its initial measurement and reduced uncertainties further. The new result in 2023, with a value of 80366.5 ± 15.9 MeV/c², aligns perfectly with the Standard Model prediction but shows a discrepancy with the CDF measurement. At this point, it was up to the CMS experiment to produce an additional independent measurement to provide more clarity.

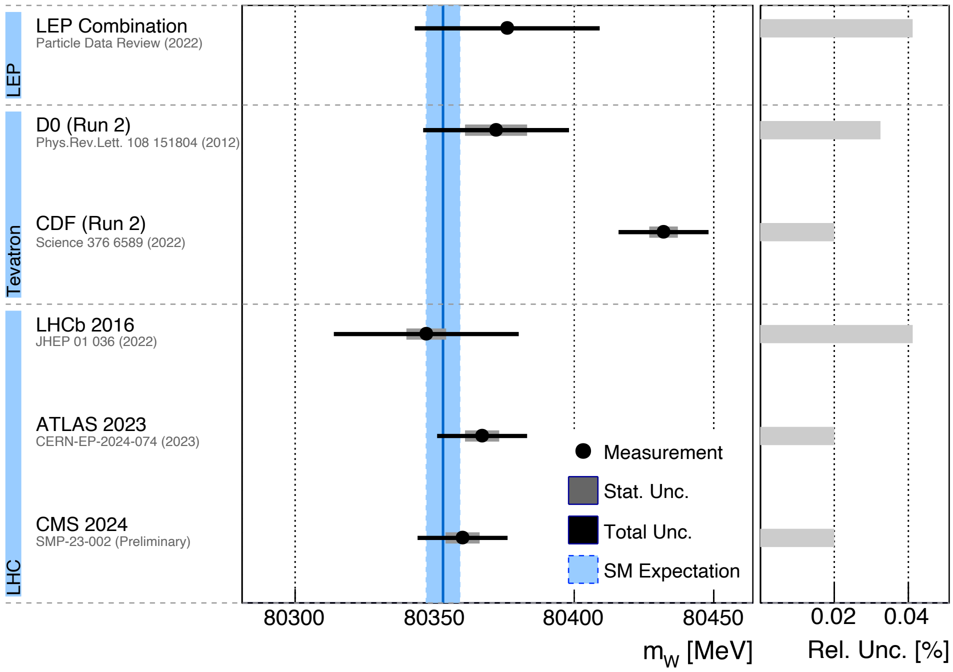

Figure 4: Summary of the most precise measurements of the W Boson Mass as well as the expectation of the Standard Model.

In September of this year, after many years of work, the CMS collaboration presented a new measurement. Unlike ATLAS, which used the decay of the W boson into electrons and muons plus the corresponding neutrinos, the CMS collaboration focused only on the decay into a muon and muon neutrino but analyzed this in many distinct measurement categories (Figure 3). As a result, CMS achieved a level of precision comparable to that of the CDF experiment. The measured value from CMS, 80360.2 ± 9.9 MeV/c², also agrees well with the Standard Model's expectations and diverges significantly from the CDF measurement. This result suggests that an unknown analysis or detector effect might be responsible for the CDF anomaly, rather than new physics beyond the Standard Model. Figure 4 shows a summary of the most precise W boson mass measurements to date, as well as the Standard Model prediction, visually representing the current situation.

A unique aspect of the CMS analysis is that the momentum was calibrated using the J/Psi meson rather than the Z boson, as ATLAS had done. This allowed for an independent determination of the Z boson mass with an accuracy of 4.8 MeV/c². While this is not as precise as previous LEP accelerator measurements, it showcases the potential for future measurements of this fundamental observable at the LHC.

Comparing the data analyses from ATLAS and CMS provides insights into the future of W boson mass measurements. While both experiments show similar systematic uncertainties, CMS achieved lower statistical errors due to a much larger dataset. Consequently, ATLAS is expected to achieve similar accuracy in the future. Overall, a combined measurement precision of 5 - 6 MeV/c², or a relative error of about 0.006 %, seems achievable at the LHC. This would surpass the theoretical prediction uncertainty for the W boson mass, which can only be improved with more advanced theoretical calculations and a better understanding of the top quark mass.

The next significant advancement in electroweak precision physics will likely require a future electron-positron particle accelerator, such as the Future Circular Collider option at CERN, which is currently discussed within the European Particle Physics community. Current studies for such a future collider suggest a potential W boson mass uncertainty of less than 1 MeV/c², almost an order of magnitude better than the most accurate current single measurements. Even more interestingly, a future electron-positron collider would also allow for a significant improvement in the precision of other electroweak observables, such as the mass of the Z boson or the electroweak mixing angle. All this information combined would enhance our sensitivity to effects from new particles with masses far beyond the reach of the LHC, potentially opening a new window to undiscovered physics.

Matthias Schott studied at the Universities of Erlangen and Cambridge and earned his doctorate at Ludwig Maximilian University of Munich, focusing on Z boson production at the ATLAS experiment. Following research stays at CERN, he led a research group at the University of Mainz starting in 2012 as part of a Lichtenberg Professorship, specializing in electroweak precision measurements, in particular the measurement of the W boson mass. His additional research interests include fundamental studies of the strong interaction and the search for axion-like particles at the LHC, supported since 2019 by an ERC grant. Since 2024, he has been a Professor of Experimental Particle Physics at the University of Bonn.