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Is physics in crisis? The mystery of the W boson.

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The standard model of particle physics [1] is the most successful theory describing the behavior of matter and energy in the subatomic realm. However, success doesn't mean perfect and a recent measurement [2] of the mass of a particle called the W boson is puzzling, as it disagrees with theoretical predictions and earlier precise measurements. If this measurement and prediction are both correct, the standard model will have to be modified or replaced, potentially overturning half a century of accepted physics.

The standard model claims that the entire physical world can be built using a mere twelve building blocks: six quarks, three electrically charged leptons, and three electrically neutral neutrinos. The six quarks are called up, down, charm, strange, top, and bottom. The top quark is much heavier than the other five. The charged leptons are the electron, muon, and tau.

The familiar world of chemistry is constructed of only a subset of the known building blocks. Two of the six quarks (up and down) are found inside the proton and neutron, and the electron is the only familiar lepton. Neutrinos are most commonly emitted from nuclear reactions, and the dominant source of neutrinos on Earth is from the sun.

In addition to the building blocks, the theory includes three known forces: electromagnetism, the strong nuclear force, and the weak nuclear force. Gravity is not included. Each of the subatomic forces are mediated by one or more force-carrying particles. The massless photon transmits the electromagnetic force, while the massless gluon transmits the strong force. For the weak force, the force carrying bosons are the very massive W and Z bosons.

Finally, the standard model includes the Higgs field, which gives mass to many of the other subatomic particles. The experimental consequence of the Higgs field is another particle called the Higgs boson [1, 3], which was discovered in 2012. The various components of the standard model are illustrated in figure 1.

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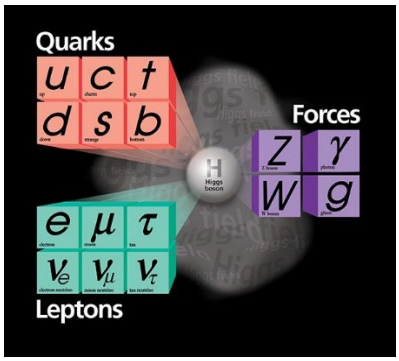

Figure 1: The standard model is comprised of quarks and leptons, and four force carrying particles. The ghostly Higgs field and associated boson round out the picture. (Figure courtesy of Fermilab.) **[end caption]**

While the standard model does a superb job of explaining the outcome of the vast majority of experiments probing the subatomic realm, there are a number of quantities that are not predicted by the theory. One set of parameters is the mass of all of the particles shown in figure 1. Instead, the various particles' masses must simply be measured in experiment and included as parameters.

While the theory doesn't predict the masses of any of the particles, it does predict the relationship between many of them. These predictions are very complicated and can only be performed using a perturbative expansion of the equations of the standard model. These perturbative approximations can be calculated to an arbitrary level of precision, although with rapidly increasing difficulty as higher order terms are included. Eq. (1) relates the masses of the W and Z bosons and to a lesser degree the rest of the particles of the standard model [4]. Arriving at this equation requires higher order perturbative corrections and the number of terms used is selected to ensure that the prediction gives a precision comparable to modern measurements. This relationship is

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{1-\Delta r} \quad (1),$$

where $\alpha \approx 1/137$ is the electromagnetic coupling constant, $G_F = 1.166\ 3787 \times 10^{-5}$ GeV^{-2}, is the Fermi constant (extracted from measurements of the muon lifetime), and Δr contains many effects including (a) the change of α as a function of energy due to the contribution of the lighter quarks, (b) contributions to the W boson component of the calculation due to top and bottom quarks, and (c) contributions to the W boson component of the calculation involving Higgs bosons. The Δr term is very complex and is difficult to express in closed form.

Thus, Eq. 1 allows researchers to combine precise predictions of the W boson and compare them to an equally precise measurement. This prediction includes the latest measurements of the Z and Higgs bosons, the top and bottom quarks, the lifetime of the muon, as well as the impact of the light quarks on the energy dependence of the prediction. In short, this comparison is a strict test of the standard model.

History

The W, Z, and Higgs bosons were all predicted in the 1960s. The W and Z bosons were discovered in 1983 at the CERN laboratory in Europe [1, 5]. The initial estimates for the mass of these particles were rather imprecise, e.g., $M_w = 81 \pm 5(total)$ GeV and $M_Z = 95.2 \pm 2.5\ (stat.) \pm 3.0\ (sys.)$ GeV. These observations led to the 1984 Nobel Prize in Physics.

In order to improve the precision of these measurements, the CERN laboratory built the Large Electron-Positron (LEP) accelerator [1] to aggressively study the properties of the Z boson. The accelerator used counter-rotating beams of electrons and positrons, tuned to collide at an energy equivalent to the mass of the Z boson. The LEP accelerator hosted four distinct detectors (Aleph, Delphi, L3, and Opal), which studied vast numbers of Z bosons. The accelerator operated from (1989 - 2000). While each detector independently measured the mass of the Z boson, it was when the four measurements were combined that the best precision was achieved. The LEP experiments measured the mass of the Z boson as $M_Z = 91.1876 \pm 0.0021$ GeV [6]. This accuracy is staggering, 0.0023%.

Towards the end of the LEP operations, the scientists raised the accelerator energy high enough to create W bosons. (The initial collision energy was set to the mass of the Z boson (i.e., 91.2 GeV), however this is not sufficient to make two W bosons, each with a mass of 80.3 GeV. From 1995 – 2000, the accelerator scientists made a series of incremental upgrades to the LEP facility, resulting in a final collision energy of 209 GeV.) The combined LEP experiments measured the mass of the W boson to be 80.412 $\pm$ 0.042 GeV [7]. Figure 3 lists the four LEP measurements, which were combined to result in this number.

However, the best measurements of the mass of the W boson came from the Fermilab Tevatron, which operated from 1985 – 2011. The Fermilab Tevatron hosted two experiments (CDF, D0), each of which made independent measurements of the boson's mass. Prior to 2022, the respective experiments' results were 80.387± 0.019 GeV [CDF, 8] and 80.375 ± 0.023 GeV [D0, 9]. This is the D0 experiment's final result (labelled "D0 II" in figure 3), but not CDF's. This CDF measurement is not represented in figure 3. When researchers combined the Tevatron and LEP measurements, the world average for the mass of the W boson was M_W = 80.385 ± 0.015 GeV [10].

The top quark is another particle whose mass has been measured very precisely. It was initially discovered in 1995 by the CDF and D0 experiments. At that time, the mass measurements were rather imprecise, e.g., M_{top} = 176 ± 8(stat.) ± 10(sys.) GeV [CDF, 11] and $199^{+19}_{-21}(\text{stat.}) \pm 22(\text{syst.})$ GeV [D0, 12]. Over the years, the measurement has improved, especially when the CERN Large Hadron Collider (LHC) began operations [3, 13]. The LHC can create top quarks at the rate of one per second. When all data is combined, the mass of the top quark is now estimated to be M_{top} = 172.9 ± 0.4 GeV [14].

The final particle that comes into play is the Higgs boson. It was discovered in 2012 at the Large Hadron Collider. The mass of the Higgs boson has been measured by both the ATLAS and CMS experiments [15]. When the two collaborations combine their measurements, they estimate the mass of the Higgs boson to be M_H = 125.25 ± 0.17 GeV [16].

These precise measurements of the mass of the W, Z, and Higgs bosons, combined with a precise measurement of the mass of the top quark and a detailed understanding of the energy dependence of the strength of the electromagnetic force, provides a backdrop for a stringent test of the standard model.

A precise measurement of the mass of the W boson

The precise measurements described in the previous section can be combined with the theory embodied in Eq. (1) to generate a precise prediction for the mass of the W boson. This prediction is $M_W = 80.357 \pm 0.004\ (\text{stat.}) \pm 0.004\ (sys.)$ GeV [17] and is represented in figure 3 by the gray bar.

The Fermilab Tevatron ceased operations in 2011 and the CDF and D0 experiments published [8,9] measurements in 2012 with uncertainties in the range of 0.020 GeV. However, these measurements did not include the entire dataset of either experiment and neither measurement benefited from the final detector calibrations nor understanding of systematic uncertainties. The two detectors are shown in Fig. 2.

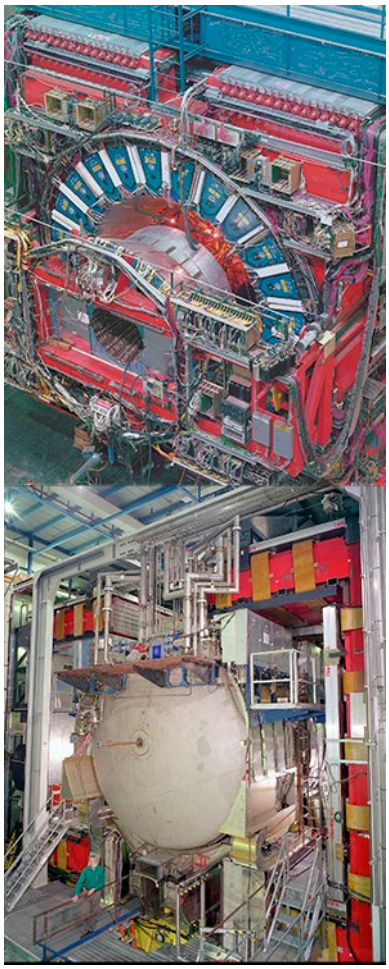

Figure 2: The CDF (left) and DZero (right) detectors were the leading particle physics detectors from about 1987 (CDF) or 1991 (D0) until 2011. The CDF experiment has published a measurement of the mass of the W boson with unprecedented precision. **[end caption]**

Given that the 2012 measurements were already very precise (of order 0.025%), improving on these measurements required incredible care and effort; indeed, it took a decade to achieve. However, in 2022, the CDF experiment released its final measurement of the mass of the W boson [2], with a value of $M_W = 80.4335 \pm 0.0064\,(\text{stat.}) \pm 0.0069\,(\text{sys.}) = 80.4335 \pm 0.0094\,(\text{total.})$ GeV. This result has achieved a precision of 0.01%. This final result is denoted “CDF II” in figure 3.

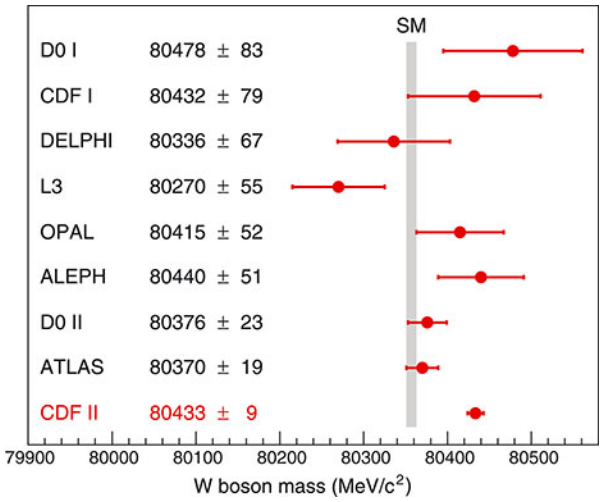

Figure 3: A summary of measurements of the mass of the W boson. The measurement described in this article is labelled CDF II, and the gray band is the standard model prediction. The other measurements are from the LEP accelerator (Delphi, L3, Opal, Aleph) and the LHC (ATLAS). The lines "D0 II" (2012) and "CDF II" (2022) are the final measurements of the mass of the W boson from the Tevatron. (Figure courtesy the CDF collaboration.) **[end caption.]**

Figure 3 illustrates the current situation. The new CDF measurement is considerably above the prediction of the standard model. The statistical significance of this difference (called sigma) is the difference between prediction and measurement, divided by the combined uncertainty. In this situation, the sigma is 6.9. Given that the accepted sigma threshold in particle physics to announce a discovery is 5.0, this result has engendered considerable interest.

What does it mean?

A seven-sigma result is usually taken to mean that the observed effect is real and not a statistical fluctuation. However, overturning or even modifying a successful theory like the standard model is not something done lightly, so it is important to consider all of the possible explanations. We have a theoretical framework and precise measurements (i.e., small uncertainties) used as input. These are compared to a different precise measurement, and they don't agree. What are the possible explanations? They are:

1. The prior measurements of the mass of the Higgs and Z bosons, the top quark, and the impact of studies of the muon properties are somehow incorrect or have an underestimate of the uncertainties;
2. The new measurement of the mass of the W boson is incorrect or has an optimistic estimate of its precision; or
3. The standard model is wrong or incomplete.

Let us take each in turn, starting with the last one. If the measurements are all accurate, the standard model will require updating. Given the theory's success, this does not mean it will need to be rejected and replaced by a new one. Instead, the more

likely explanation would be that the overall framework of the standard model is correct, but some additional forces or particles will need to be added to it. Because the theory correctly predicts most data, we can infer that the forces involved are very weak and/or the masses of the overlooked particles or the energies at which they come into play are high. Possible explanations include supersymmetry [18], dark matter [19], additional Higgs bosons [20], or any number of other proposed fields and symmetries. More detailed descriptions can be found in Ref. [2], especially references 11 – 24 therein.

On the other hand, perhaps the explanation is more prosaic. For possibilities (1) and (2), we could consider the possibility that the individuals making these measurements just weren't up to the task; however, the research groups are all highly respected in the field, often with illustrious careers. Furthermore, each group consists of many individuals, all expert, and all double checking each other. While it is possible that such groups can make mistakes, if they did, the mistakes are subtle.

It might have been possible for the D0 experiment (the CDF experiment's cousin at the Fermilab Tevatron) to also make an improved measurement of the mass of the W boson; however, it was determined that the detector had experienced radiation damage induced by years of operation. This damage was an insuperable obstacle to improved measurements. Therefore, there will be no forthcoming D0 measurement to confirm or falsify the CDF measurement.

Thus, the only way to double check all of the measurements, would require that researchers utilize currently operating particle accelerators and the only accelerator that has the energy to generate the relevant particles (W & Z bosons, Higgs boson, top quarks) is the Large Hadron Collider.

And that is a problem. The problem is not that the LHC cannot generate lots of the particles in question; on the contrary, the LHC can generate them in vast quantities. The problem is not that the particle detectors at the LHC aren't up to the task; on the contrary, the CMS and ATLAS detectors are both excellent, with astonishing capabilities. The problem is something else, and it's a pernicious one.

In order to measure the mass of particles with the required precision, one needs to have the best data, with the least amount of instrumental noise and effects which can degrade the result. And the LHC does not operate under those conditions. Indeed, the LHC is operated as a discovery machine, which means scientists need to study as many collisions as possible. To do this, the LHC beams are configured so that many collisions occur simultaneously. When the beams are operating at maximum brightness, each time the beams pass through one another, on average something like 50 collisions occur.

While that's a lot, most collisions are only glancing ones, which means that it is usually possible to identify which of the 50 was a head-on collision and thus which collision is interesting to study. But those 49 other collisions all generate particles which also hit the detector. Because these extraneous particles are low energy, they do not affect

most measurements, but they do muddy the water for very precise ones. Recall that the CDF high precision W boson mass measurement has a quoted uncertainty of 0.012% and that the aggregate LEP measurement of the Z boson has a quoted uncertainty of 0.0023%. It is very difficult for the LHC experiments to achieve that level of precision in the messy environment in which 50 simultaneous collisions occur.

It would be possible for the LHC accelerator to reduce the number of simultaneous collisions so that only a few occur with each beam crossing. This would allow the LHC experiments to measure the mass of the W and Z bosons precisely. However, to achieve the precision of earlier measurements would take years of data collection to achieve and, during the time in which the reduced beam was supplied, the LHC would have fewer high energy collisions to look for rare and unexpected phenomena.

Thus, given the LHC's focus on discoveries, which requires a tremendous number of collisions, it is extremely difficult for the LHC to measure the mass of the W boson with the precision reported by CDF. To give some context, the LHC began operations in 2011 and the CMS experiment has still not reported a W boson mass. The ATLAS experiment reported such a measurement [21] in 2017 of $M_W = 80.370 \pm 0.019$ GeV. This measurement only used the data taken in 2011, and the uncertainty is twice as large as that recently reported by CDF.

While both the ATLAS and CMS experiments continue to work diligently to make a measurement of the mass of the W boson, it may be that the effects of multiple simultaneous collisions are insurmountable.

So, where does this leave us? It leaves us in a significant predicament. Currently operating particle accelerators have not been able to validate or falsify the CDF measurement of the W mass. The only way to crosscheck the result is to build a new particle accelerator – one that collides electrons and positrons together at high enough energies to make, for example, pairs of W bosons (i.e., $e^+e^- \rightarrow W^+W^-$). Only then will this mystery be resolved.

Plans for an electron/positron collider with these capabilities are being drawn up [22], however if such an accelerator is ever built, it will not begin operations before 2040, at the earliest. We are left in the unfortunate predicament that we have a mystery which will puzzle scientists for decades.

It is often true that scientific mysteries take a long time to solve. Discovery of the Higgs boson took about fifty years, and the observation of gravitational waves took nearly a century. We may just have to wait to find out the significance of the CDF measurement of the mass of the W boson – including the possibility that the discrepancy will turn out to be an unexplained mismeasurement. Or it could be the key clue that changes everything. Only time will tell.

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