W-boson mass hints at physics beyond the standard model

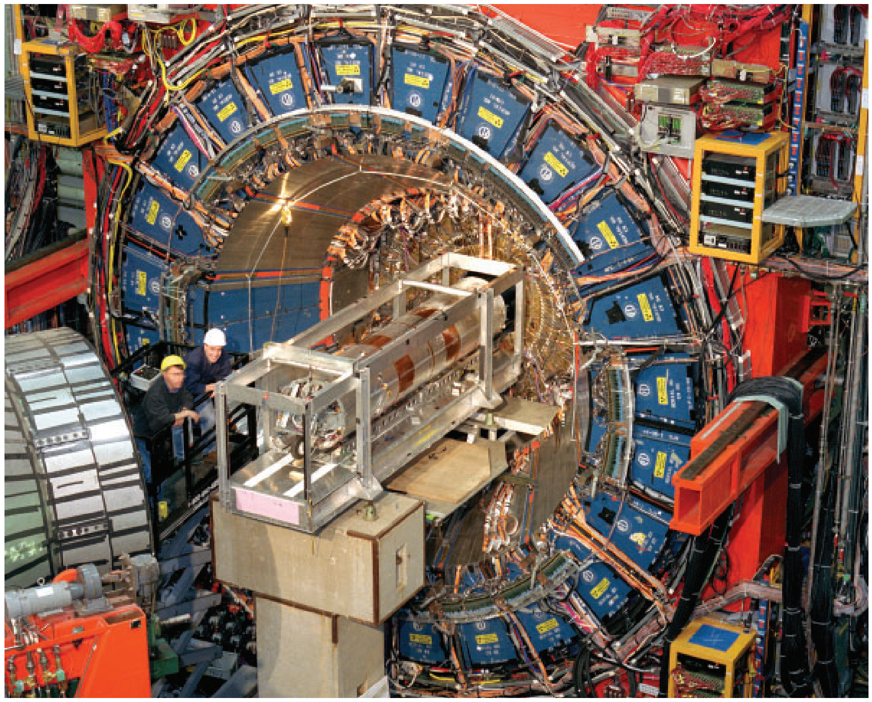

FIGURE 1. THE COLLIDER DETECTOR at Fermilab's now-defunct Tevatron accelerator measured the positions and momenta of electrons and muons produced in proton–antiproton collisions as they passed through 30 240 high-voltage wires. The detector provided data for the highest-precision measurement of the W-boson mass to date. (Courtesy of Reidar Hahn/Fermilab.)

Nearly a decade of collisions and a decade of analysis yield the fundamental particle's mass with the highest precision to date.

The standard model of particle physics must be incomplete. It doesn't explain gravity or dark matter, among other phenomena. But the model does an excellent job describing the other basic building blocks and forces of nature, and measurements that violate it are hard to find.

That's why it was big news last year when the Muon $g-2$ collaboration at Fermilab found that the muon's magnetic moment anomaly differs from the standard-model value by 4.2 standard deviations (see PHYSICS TODAY, June 2021, page 14). Although a substantial difference, it fell short of the 5 standard deviations that are canonically required to claim a discovery.

In April the Collider Detector at Fermilab (CDF) collaboration published a result that surpasses that threshold and challenges the standard model. Using the now-shut-down Tevatron collider, the 400-person collaboration measured a W-boson mass that is 7 standard deviations higher than predicted and more precise than all previous measurements combined.[1] If independently confirmed, the result points to physics beyond the standard model.

W is for weak

Alongside the Z boson, the positively and negatively charged W bosons are the mediators of the weak nuclear force; their role is analogous to the photon's in the electromagnetic interaction. The weak force is responsible for beta decay, and without it the Sun wouldn't burn. Emitting or exchanging a W boson is also the only way quarks can change their flavor. The W-boson mass is tightly constrained by many other parameters, particularly the masses of the Z boson, Higgs boson, and top quark. Those interdependencies make the W-boson mass a strong test of whether the standard model is self-consistent.

The W boson's existence and properties were predicted in the 1960s and confirmed experimentally at CERN in 1983. Although the standard model doesn't give the mass of the W boson (or any other particle) directly, if one knows the experimental values of enough related particle masses, then predictions become possible. In the past, for example, W-boson-mass measurements enabled predictions for the masses of the top quark, which was eventually measured by Fermilab in 1995, and the Higgs boson, which was measured at the Large Hadron Collider (LHC) in 2012 (see the article by Joe Lykken and Maria Spiropulu, PHYSICS TODAY, December 2013, page 28).

The observation of the Higgs boson was the final piece of the standard-model puzzle. It also presented the opportunity to check if the W-boson mass agreed with the model. The Z-boson mass was already known precisely—the world average is 91 187.6 ± 2.1 MeV—and with the Higgs mass as a final input, the standard model could offer a concrete number: a W-boson mass of 80 357 ± 6 MeV, with the precision limited by the mass inputs and the number of terms used in the perturbative calculations.[2]

Previous experimental values for the W-boson mass have more or less agreed with predictions.[3] For example, combined previous measurements from the Large Electron–Positron Collider and earlier Tevatron measurements yielded a value of 80 385 ± 15 MeV. Similarly, in 2017 the ATLAS Collaboration at the LHC found a mass of 80 370 ± 19 MeV. But none of those measurements rivaled the precision offered by the standard model. A precise measurement of the W-

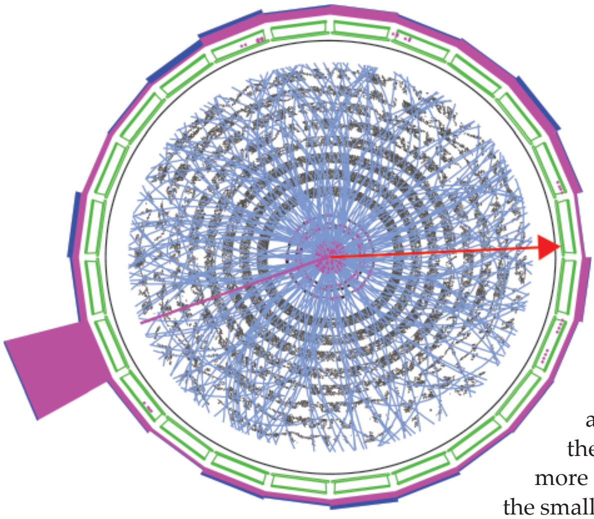

FIGURE 2. ELECTRON AND NEUTRINO PATHS (pink line and red arrow, respectively) from W-boson decay are picked out of the chaos of pion and kaon signals (blue curves). Particle positions—except those of the neutrino, which are inferred from momentum conservation—come from the electrical signals (black dots) of the cylindrical collections of high-voltage wires in the detector in figure 1, which are shown here in cross section. Calorimeters (outermost pink and blue rings) measure energy; the wedge of the lower-left azimuth shows a peak signal from the electron. The momentum distributions of carefully selected and measured electrons and muons can be fitted with a theoretical model to find the W-boson mass. (Courtesy of Ashutosh Kotwal.)

boson mass was one of the CDF collaboration's main goals for the Tevatron's second run.

Decades in the making

The Tevatron in Batavia, Illinois, propelled protons and antiprotons in a four-mile loop and was the most powerful particle accelerator in the world for about two decades until it was unseated by the LHC in 2009. Its first run, from 1992 to 1996, included the discovery of the top quark. Its second run extended from 2001 to 2011, after which the Tevatron was permanently shut down (see Physics Today, March 2011, page 33). Over that operating lifetime, researchers developed and refined techniques for precisely calibrating the CDF, shown in figure 1. They also improved their criteria for selecting data.

The CDF collaboration published a W-boson mass measurement in 2007 and another in 2012 with improved precision, mentioned previously.[4] Those results relied on data collected in the early years of the Tevatron's second run. For the new result, drawn from the full data set collected between 2002 and 2011, the researchers selected more than 4 million W bosons produced via quark–antiquark annihilation, a sample four times as large as that used for the 2012 analysis. In part because of the large sample size, the researchers attained a precision that's a factor of two better than previous studies at any collider. Although the LHC has already measured far more W-boson events than Fermilab, the Tevatron benefitted from lower collision energies, which limit particles' momenta to ranges easier to model theoretically.

Although including more data generally offers improved precision, the CDF researchers found it more advantageous to select only the small fraction of the total produced W bosons that could be measured precisely. The W boson decays into a neutrino paired with either an electron or a muon. Electrons and muons above a certain energy threshold and within a particular momentum range were more likely to be from pure W-decay events. Those and other criteria helped researchers select unambiguous W-boson candidates with low backgrounds.

The CDF tracked the electrons and muons as they passed through 30 240 high-voltage wires around the collision site, as shown in figure 2. One of many ways the CDF collaborators improved the accuracy of their results was by obtaining precise, micrometer-scale information about the positions of the wires. For example, if the straight paths of cosmic rays didn't show up as straight in the detector, the information about the wire positions must've been wrong and was corrected.

The researchers then measured the electron and muon momentum distributions, which are related to the mass of the W boson. Neutrinos are impossible to detect at hadron colliders, but their momenta, also needed for the mass measurement, could be deduced from momentum conservation: Before the collision, the momentum perpendicular to the beam is zero, so after the collision, the sum of all resulting particles' transverse momenta must be zero.

Then began a decade of rooting out sources of errors with 15 new or improved analyses and techniques. The CDF team members offset each electron and muon momentum distribution data set by an encrypted, randomly selected value between −50 MeV and 50 MeV to avoid the potential for subjective bias in fitting. They fit their data with a custom Monte Carlo simulation that models the movements of the electrons and muons through the detector. Compared with the 2012 result, the simulation had an improved precision, in part because of new information about the proton structure and knowledge extracted from the CDF data about how W bosons interact with other particles.

Weighty implications

In November 2020, the team decrypted the offset and unveiled the W-boson mass measurement, which was the most precise to date. "We were so focused on the precision and robustness of our analysis that the value itself was more like a wonderful shock," says Ashutosh Kotwal of Duke University, who initiated and led the analysis.

The researchers obtained a W-boson mass of 80 433.5 ± 9.4 MeV, well above the value from the standard model (see figure 3) and five of the eight previous measurements, although it falls within the uncertainty of some. The CDF team also measured the Z-boson mass, which did agree with the world average. That step wasn't taken in previous measurements of the W-boson mass and was one of many demonstrations of internal consistency.

The observation, if confirmed by independent measurements, could indicate unknown particles or forces. "Now we have to try and understand whether the theory is missing something or whether the measurement could be off or too optimistic about its uncertainty," says Martijn Mulders of CERN, who wasn't involved in the new study. Jonathan Lee Feng of the University of California, Irvine, who also wasn't part of the CDF collaboration, agrees that the result isn't definitive. But he adds, "it is highly significant and written by people and a collaboration with excellent reputations who have performed this analysis over 10 years."

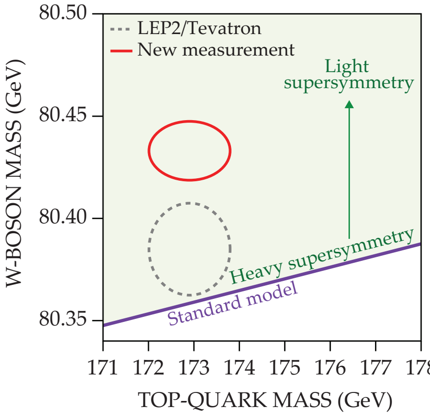

FIGURE 3. THE W BOSON is correlated to other masses in the standard model of particle physics. Using the measured Higgs-boson mass, the model predicts W-boson and top-quark masses to take values anywhere on the purple line. Experimental W-boson masses vary in how well they agree with the prediction, as shown by the 68% confidence level of the new Tevatron result (red) and the combined Large Electron–Positron Collider and earlier Tevatron measurements (dashed gray). The gap between theory and experiment could be bridged by many extensions to the standard model. For example, supersymmetry can shift the predicted masses to any value in the green region given the right parameters. (Adapted from ref. 1.)

With the Tevatron closed for business, the CDF collaboration is necessarily done collecting data. "We will engage in discussions with our colleagues on other experiments to see if we can come up with more ideas for improvement," says Kotwal. "In parallel, we hope that the ideas we have published can help other experiments perform a similarly precise measurement of the W-boson mass."

The LHC went offline in 2018 but will resume measurements this summer with higher beam energy and collision rates and with better detectors. Future W-boson measurements could also happen at proposed electron–positron colliders, such as the International Linear Collider in Japan, the Future Circular Collider at CERN, and the Circular Electron Positron Collider in China (see PHYSICS TODAY, September 2020, page 26).

Possible explanations for a larger W-boson mass come from extensions to the standard model—such as a composite Higgs boson, additional Higgs-like particles, dark-matter particles, or supersymmetry. Such extensions would increase the expected W-boson mass through new interactions, but despite extensive searches, no indications of those particles or interactions have been found so far. And although those extensions could reconcile the standard model with a larger W-boson mass, getting them to do so without causing inconsistencies with other predictions may prove nontrivial.

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