Upsetting the Standard Model of Physics

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The W boson controls the Sun's energy output - slightly more or less and the Earth's surface would be fried or frozen. One could say that life on Earth depends on the W boson.

My paper titled "High-precision measurement of the W boson mass with the CDF II detector" was published as the cover story in the world's most prestigious journal Science on April 7, 2022, brought out by the American Association for the Advancement of Science (AAAS). Our team of 400 scientists at the Fermi National Accelerator Laboratory (Fermilab) has been working on the analysis of fundamental particles called W bosons produced at the Tevatron particle accelerator in the CDF II experiment for the last 10 years. In November 2020 at a meeting on ZOOM we decrypted the result on the mass of the W boson. The result was a pleasant shock for us. We had worked till then on encrypted data so that the numbers should not influence our analysis. The central value and the uncertainty of the latest mass measurement is $80,433 \pm 9$ MeV/c^2, where c is the speed of light in vacuum. Compared to the predicted mass of $80,357 \pm 6$ MeV/c^2 from the Standard Model theory, it is nearly 77 MeV/c^2 higher. In the language of statistics, this disagreement has the significance of 7σ, meaning that the chance that this difference is a random statistical fluke is less than one in a billion. The scientific community conventionally accepts a significance of 5σ, or the chance of a fluke lower than one in 3.5 million, that the physicists must clear to claim a definitive discovery.

The new measurement of the W boson mass is the most precise measurement ever made of this fundamental quantity. It provides a rigorous test of the Standard Model; a set of equations, developed between the 1940's and the 70's, that describe the basic building blocks and forces of nature. The SM model has been one of the most important theories in all science. Over the last 70 years, of the 161 Nobel prizes awarded in all branches of physics, 49 of them, or 30% of the prizes were awarded for contributions to the Standard Model of physics.

Our measurement is significantly different from the theory. This could indicate a new principle at work in nature. The new measurement of the W boson mass is our biggest clue yet that we do not completely understand the weak nuclear force or all the particles that experience this force. This is reminiscent of a similar disagreement observed with classical physics a century ago - the observation of the atomic nucleus by Rutherford - which paved the way for the emergence of quantum mechanics and defined modern physics. Therefore, this upset to the Standard Model may well point towards exciting new discoveries in particle physics for years to come.

For the latest development we had a large sample of 4 million W bosons collected during the entire CDF II run from 2002 till 2011. We used established techniques from previous analyses but more importantly, we developed many new analysis techniques that eventually paved the way for this discovery. We implemented new ideas to use our data in novel ways to calibrate our experimental apparatus much more precisely than in the past. We also incorporated new information about the colliding protons' structure that the particle physics community has collected over the decade. Importantly, our analysis procedure demonstrates a number of precise checks of internal consistency, which no other experiment has demonstrated at this level. The combination of four times larger dataset, more insightful methods and ideas of using the data, and new information about the proton structure allowed us to improve the precision of this measurement substantially.

In this paper we have described fifteen new ideas or improved techniques which were developed over the last 10 years, since our 2012 publication of the W boson mass. That measurement, which had an accuracy of 0.02%, predicted the range of the mass of the Higgs Boson before its discovery at the Large Hadron Collider (LHC) at CERN in Switzerland. In the latest publication of 2022, we have improved the accuracy by another factor of two, to an unprecedented 0.01%.

There is another factor which led to a more precise measurement than all other previous measurements combined. I devised a method of using cosmic rays to pin down the positions of 30,240 sensor wires, each within a precision of one micron. These high-precision sensor wires, placed at high voltage in a gaseous volume, record the passage of electrons and muons coming from the W boson decay. We used the data from these sensors to measure the momentum of each election and muon with an accuracy of 0.004%.

Understanding such a large volume of data with extreme precision is always challenging. Every time we were faced with a puzzle, our philosophy was to leave no stone unturned until the mystery was solved. The journey felt like a treasure hunt. We were so focused on the precision and robustness of the analysis that the value itself of the W boson mass, when it was decrypted, was more like a wonderful shock. Not only is our new measurement much more precise than all other measurements but it also demonstrates rigorous consistency checks. For example, we also measure the Z boson mass in both electron and muon channels and find agreement with the LEP (Large Electron Position) collider's measurement at CERN. No other measurement of the W boson mass has performed this consistency check.

Having so far talked about the importance of the W boson mass, let me introduce you to the special characteristics of this elusive entity. Of the basic principles that physicists use to describe the beginning of the Universe, the W boson is one of the most important. Understanding it and its behavior is central to particle physics. It is a quantum-mechanical mediator of the weak force, one of the four known forces in nature. Even today the existence of the world is dependent on the W boson having a large mass. For example, the nuclear fusion of four protons into a helium nucleus is the reaction that powers the sun. The reaction requires the conversion of protons into neutrons by the weak force at just the right rate, which is possible because the W boson has a large mass. This is one of the most important aspects of the Universe that is crucial for our existence. Knowing it well proves useful in a host of other investigations in nuclear physics and astrophysics, such as the creation of all heavy elements, including gold. Furthermore, the radioactivity induced by the weak force releases enough energy in the Earth's mantle to keep the Earth's iron core molten, generating a magnetic shield that protects all life on Earth from lethal solar radiation.

To establish new physics like supersymmetry, it was necessary to measure the mass of the W boson with as high a degree of accuracy as possible. The value of the W boson mass in nature is influenced by yet-unknown particles through quantum vacuum fluctuations. All known particles, including top quarks and Higgs bosons are involved in these vacuum fluctuations. If supersymmetric particles exist, they will also participate in these fluctuations and cause an additional small change in the W boson mass. With the conjecture of supersymmetric particles, the predicted mass of the W boson could increase by up to 80 MeV/c^2 relative to the Standard Model theory prediction, depending upon the properties of the new particles.

Similar calculations have been performed assuming the existence of additional Higgs-like bosons, a fifth force, or dark-matter particles, which also change the W boson mass by a similar amount. These examples illustrate how the predicted mass of the W boson changes from theory to theory. The power of the W boson mass measurement arises from its ability to adjudicate between these different hypotheses, to pass judgment and select the one closer to the truth, so to speak. The more accurate the measurement, the closer to the truth one can hone in.

Thus, establishing the mass of the W boson with utmost accuracy and comparing it with predicted values from different theories is instrumental in going beyond the Standard Model theory and treading the path of new physics. It would offer proof for or against what had been conceptualized around the interactions of particles and forces at the subnuclear level. The latest mass measurement motivates an extension of our conceptual understanding at the fundamental level.

I have initiated and led the analyses to measure the W boson mass precisely in the CDF II experiment at Fermilab. Over the last 27 years, I have published five world-leading measurements of the W boson mass. The present measurement is the most significant deviation ever observed from a fundamental prediction of the Standard Model of physics.

One of the primary goals of the Tevatron Run 2 ($1999 - 2011$) was to perform a precise measurement of the W boson mass. My group developed and refined the techniques for performing precise calibrations of the CDF detector over the last two decades, starting in the early 2000's. In parallel, the criteria for selecting the data for analysis were tuned up. Thirdly, we wrote sophisticated simulation codes to incorporate the minute details of the experiment and known physics effects. Prior to the 2022 publication, CDF published W boson mass measurements in 2007 and 2012, using subsets of the complete dataset and using state-of-the-art analysis techniques at the time.

The data from the CDF II experiment has been fully analyzed. We will engage in discussions with our colleagues on other experiments, to see if we can come up with more ideas for improvement. 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 experiments at the LHC have collected and are continuing to collect a lot of data. Even though the W bosons at LHC are produced slightly differently than the Tevatron, because the LHC is a proton-proton collider and the Tevatron was a proton-antiproton collider, the LHC experiments have the opportunity to make this measurement. If a new electron-positron collider is built, it can measure the W boson mass even more precisely.

The theoretical physics community is taking a close look at the calculations. They are already exploring extensions of the Standard Model, that could bring the theory in line with our measurement. These ideas could motivate a new round of experiments that would be sensitive to the new physics. Hunting for new particles is indeed an excellent method to follow up with. The LHC as well as smaller, specialized experiments are sensitive to the kinds of new particles and interactions that can influence the W boson mass. If there is new physics which could explain the difference of our result from the SM expectation, then the new physics could show up directly in these experiments. Looking for rare processes or processes forbidden by the Standard Model could also provide additional evidence of new physics. A new electron-positron collider would enable ultra-precise measurements and searches for rare processes in a different environment than the proton-proton collisions at the LHC.

In parallel, my group is looking to the future. I am pursuing the hypothesis that dark matter consists of particles. According to certain extensions of Standard Model, such particles could be produced at the LHC. Since their signature would be incredibly fleeting, it is a technological challenge to capture the traces of particles that disappear in a billionth of a second into dark matter. I am designing electronic circuits that could capture the fleeting images created by such processes. These circuits will perform the task of identifying dark-matter production hundreds of times faster than traditional computers. I have published two papers describing these ideas, the latest one in the prestigious Nature journal. I am working with a team of eight undergraduate students from computer science, engineering, mathematics and physics on this design project.