MIT physicists use precision with the CMS detector to resolve the puzzle of the W boson mass

In today's seminar at CERN, Joshua Bendavid, a research scientist from the Massachusetts Institute of Technology (MIT, PhD 2013), presented an exciting breakthrough by the CMS experiment at the Large Hadron Collider (LHC). The highly anticipated precision measurement of the W boson mass has been in the making for over a decade and was supposed to bring clarification to the mystery sparked by the 2022 W boson mass measurement of the CDF collaboration at the Fermilab Tevatron collider [CDF Paper]. The CDF measurement left the community excited and puzzled, with a measured value substantially larger than the prediction. Thanks to significant improvements to the analysis techniques, the CMS team was able to produce a result that matches the precision of the CDF result and is substantially more precise than all previous measurements.

The W boson, first discovered in 1983 at CERN [UA1/2 W observation], is a key particle in the standard model and explains how particles interact and how the forces that hold everything together -like electromagnetism and the weak force- are related. Measuring its mass with high precision is important because it probes the self-consistency of the standard model. Over the years, 10 different experiments have measured the W boson mass, but the new CMS result sets a new benchmark, achieving a precision of 1 part in 10,000.

"The new CMS result is unique because of its precision and the way we determined the uncertainties," said Patty McBride, a distinguished scientist at the US Department of Energy's Fermi National Research Laboratory and the CMS spokesperson during the analysis. “The entire universe is a delicate balancing act,” said Anadi Canepa, the current deputy spokesperson of the CMS experiment and a senior scientist at Fermilab. “If the W mass is different from what we expect, there could be new particles or forces at play.”

The MIT team from left to right: Jan Eysermans, Joshua Bendavid (speaker), Christoph Paus and Kenneth Long. Not in this picture are Tianyu Justin Yang and Guillelmo Gomez-Ceballos.

MIT physicists played a crucial role in this achievement, working with researchers from across the U.S. and Europe. The MIT team led by Professor Christoph Paus consists of MIT researchers, postdocs, and a graduate student who made key contributions to bring the project to completion. In early 2023, MIT hosted a dedicated hackathon, bringing together the physicists involved to fine-tune their strategies and complete the final stages of this highly complex analysis.

When the W boson is created in a proton-proton collision at the LHC, it quickly breaks apart into other lighter particles. This analysis used only the W boson decay into two particles: one we can see (a muon) and one we cannot see (a neutrino). The CMS team thus zeroed in on the muon only, measuring it with extraordinary precision to extract the W boson mass. “Neutrinos are notoriously difficult to measure,” explains Joshua Bendavid, who directed the analysis team. “In collider experiments, the neutrino goes undetected, and so we can only work with half the picture.”

The analysis was built on a large dataset – 300 million events recorded from the LHC’s 2016 run and another 4 billion simulated events. From this dataset, about 100 million W boson candidates were selected and used to measure the mass. The team used advanced simulations, even accounting for microscopic shifts in the detector as tiny as the width of a human hair. For the recalibration of the momentum scale, the very precisely known J/psi resonance decaying to two muon tracks was used. The calibration sample contained another 100 million particle tracks. A first recalibration typically improves the default resolution by a factor of 10 but with this entirely new method, the muons can be measured more accurately by another factor of 20, to 1 in 50,000.

To infer the W boson mass value from the hundreds of millions of muon momentum measurements, the minute theoretical details of the W boson creation in the proton-proton collision as well as its decay to a muon and neutrino have to be precisely understood and modeled. To do this, the team incorporated the newest and most advanced theoretical predictions into their simulations and used prescriptions to further refine the models using the vast amount of data available from the experiment. “Our theoretical approach differs fundamentally from other experiments that used the Z boson to calibrate their theoretical models. Instead, we exploit the latest advances in theoretical predictions, together with their uncertainties, which we validate and improve using our data”, says Kenneth Long, a postdoctoral researcher at MIT and a core member of the analysis team. The Z boson, which is like a twin to the W boson, is easier to measure because it decays into two visible particles (for example two muons). The CMS team used the Z boson just to double-check both their experimental and theoretical inputs, providing strong confidence in their methods.

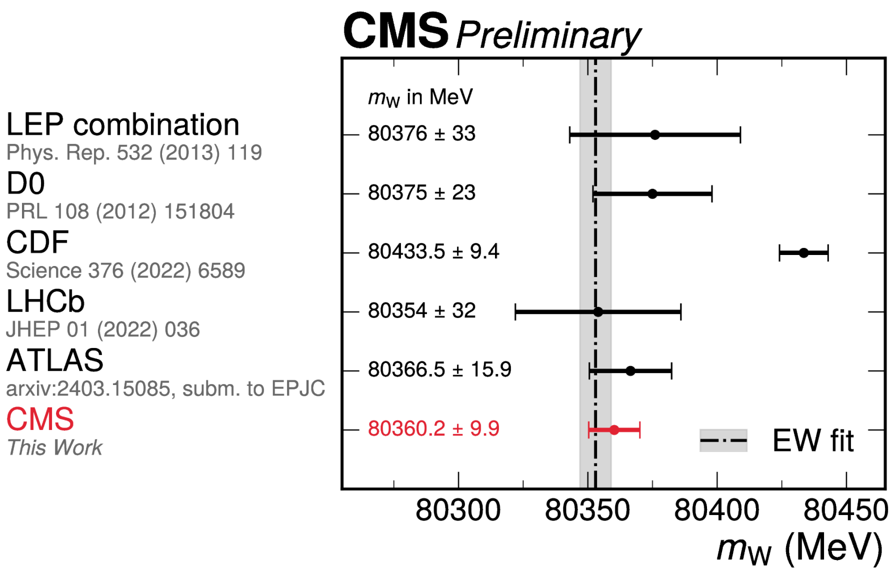

Figure 1. Comparison of various measurements of the W boson mass, including in red the new measurement by the CMS experiment [CMS].

The last step involved a detailed statistical analysis to extract the W boson mass. The result of 80360.2 ± 9.9 MeV fits perfectly with predictions from the standard model (80353 ± 6 MeV), reaching an impressive accuracy with an uncertainty of 9.9 MeV (see figure). The result is consistent with all other measurements, but it is in clear tension with the CDF measurement and thus the mystery is resolved.

The timing could not have been better—this breakthrough came just in time for MIT graduate student Tianyu Justin Yang's thesis defense to make the summer cutoff for handing in his thesis. "It has been my honor to contribute a verse to this powerful play, which reached its curtain call just before I submitted my doctoral thesis, now set to be released following a publication embargo."

Even with this remarkable milestone, the team's work is far from done. They are already preparing for the next stage of research, which will aim to achieve even greater precision in measuring the W boson mass. This time, the focus will shift to the elusive neutrino, the invisible part of the W boson decay process. By exploring this less accessible aspect, the team hopes to refine their measurements and further challenge established theories. "We now have an opportunity to investigate different facets of the W boson's behavior by studying the other half of its decay by inferring the neutrino momentum from the momentum imbalance in the entire event", says Jan Eysermans, a postdoctoral researcher at MIT and also one of the core members of the analysis team.

The measurement of the W boson mass is one of several recent precision measurements which rival or in this case far exceed the precision reached with the large electron-positron (LEP) collider, which ran in the same tunnel before the LHC and was generally considered the ultimate precision device. "This measurement is one of many precision measurements that the LHC will produce in the years to come. I would have never thought that a hadron collider could eventually become more precise than LEP," says Paus who worked on the LEP collider in the nineties.

[CDF paper] CDF Collaboration, *Science* **376** 170 2022
[UA1/2 W observation] UA1 Collaboration, G. Arnison et al., Phys. Lett. B 122, 103 (1983); UA2 Collaboration, M. Banner et al., Phys. Lett. B 476, 103 (1983)
[CMS] CMS Collaboration, https://cds.cern.ch/record/2910372