# W boson mass discrepancy as a probe of the fundamental laws of physics

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You may have heard of the Standard Model (SM) of particle physics, perhaps not knowing what it is. Roughly speaking, it is the theory that defines how all the known particles such as electrons, photons, and so forth interact with each other. One can write down the equation within a minute, yet out of it can be made an unprecedented number of predictions with extraordinary accuracy, so much so that there seems nothing left to be uncovered by particle physicists.

In fact, this is not the case. Some astronomical observations suggest that there is room for improvement in the SM. One problem is that there is more matter than can be seen in the universe to explain several kinds of gravitational effects that occur inside galaxies. These invisible particles—dark matter—are not included in the SM, and therefore call for an extension of the model.

Here comes a challenge. One can come up with many mathematically possible models which describe missing matter. Of course, there are properties a plausible model may possess: symmetry and simplicity. These principles will rule out some, but still, quite a few candidates remain. For scientists to identify the model consistent with reality, the accumulation of more experimental data is a must.

In April 2022, a surprising announcement was made by Fermilab. The mass of the W-boson, a short-lived particle in the SM, has been measured with incredible precision, and even more astonishing, it did not coincide with the prediction. They estimated the mass of such ephemeral—the nature which makes it impossible to measure the mass directly—particles by instead measuring the energy and momentum of particles into which the W-boson decays; they are usually more stable. The famous laws of energy and momentum conservation then tell you the original W-boson's mass. According to the SM, the W-boson mass is $80.357 \pm 0.006$ GeV, while the new measurement confirmed that it is $80.4335 \pm 0.0094$ GeV. Technicalities of unit aside, this discrepancy is statistically significant, meaning that it is a strong indication of new physics.

Indeed, this result might turn out to be flawed: a mistake in the process of the experimental setup or data analysis could result in a critical systematic error. However, the analysis is based on the collection of 10-year-old data and is said to have been carried out with lots of calibration cross-checks with other measurements. The result was likely a genuine experimental anomaly.

If we believe the result of the new measurement, how do we compensate for the mass discrepancy? Can the mass of the W-boson be influenced by dark matter? To answer these questions, one needs to understand how the mass of a particle is generated. In short, the Higgs particle is thought to be responsible for imparting mass to all known particles. This would imply that adding another Higgs-like particle would give rise to a change in the mass spectrum. In fact, the simplest possible solution is to include another Higgs particle.

The second possibility that the W-boson receives additional mass is through quantum correction by a new kind of interaction. Counterintuitive as it may sound, the mass of a particle is dependent on that of other particles with which it can interact. This new interaction can be mediated by a new particle, the so-called dark photon, just like photons for the electromagnetic interaction.

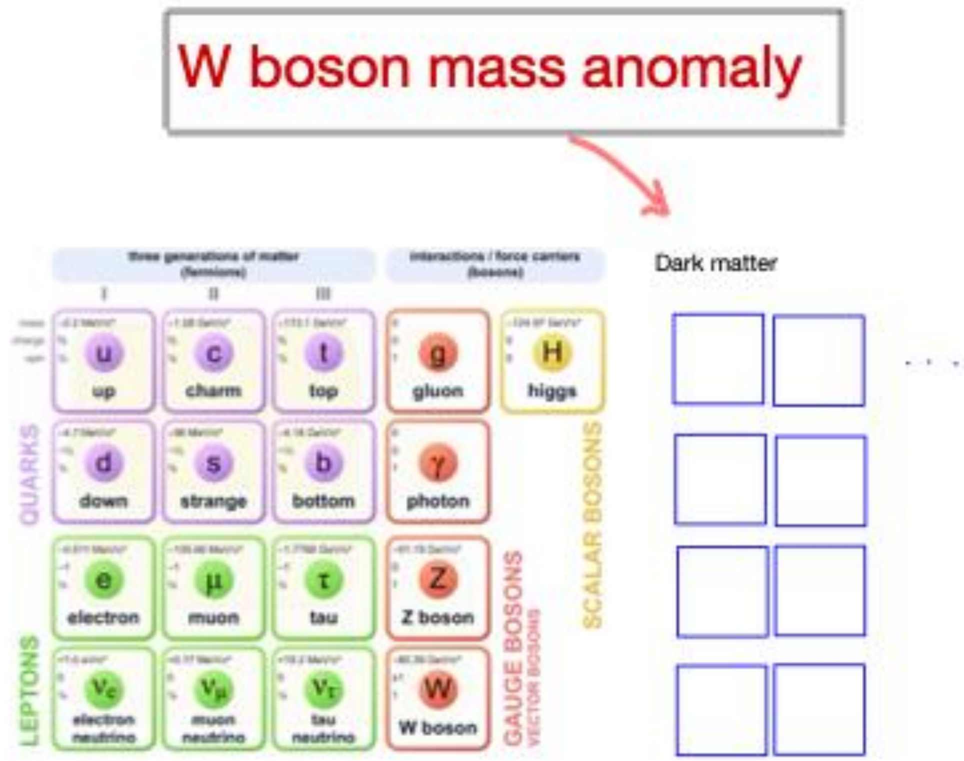
The aforementioned solutions are somewhat simple. As noted earlier, however, symmetry is also a good viewpoint from which we think of a new theory. Among such explanations is supersymmetry. Supersymmetry is a property of a class of models, each of whose particle has its partner particle. In the SM case, supersymmetry would give each particle shown in the figure below another particle, thus making the total number of particles double. These rich degrees of freedom allow one to think of various modifications of the W-boson mass predicted by the SM, many of which boil down to much the same mechanisms elaborated on in the previous paragraphs.

One might wonder what the point of supersymmetry is; indeed, it looks so complicated to solve this anomaly itself. As a matter of fact, there are many technical motivations behind this symmetry. Here, I would like to introduce a wonderful implication of it. Supersymmetry is proven to be the only possible extension of geometric symmetries. A prime example of such geometric symmetries is translational symmetry. We take it for granted that the same laws of physics apply everywhere: you and your friend living far away from each other can still agree with Newton’s laws of motion. Supersymmetry, counterintuitive as it may seem, is also related to such geometry, and if it exists, will reveal the aesthetic nature of reality hinting that our intuitive notion of spacetime is not fundamental.

As you can see, this new finding seems explicable in many scenarios, and therefore more research is urgent to figure out which one correctly describes our real world. That work requires testing models with an enormous amount of experimental data. Since the publication of the discovery, dozens of papers regarding the anomaly have already come out. I believe, however, that more attention and dedication should be made to the finding. As the SM makes so many predictions consistent with experiments, anything which disagrees with it is precious fuel for research.

In summary, the triumph of the SM is not the end of the quest for what the universe is, and how it works. The W-boson anomaly can be a clue to both dark matter and the underlying symmetry.

No one knows what dark matter actually looks like, not in the sense that it is essentially invisible, but that it might exhibit some exotic behavior physicists have never imagined. Likewise, the discovery of supersymmetry might unravel another aspect of reality we humans cannot intuit, just like quantum mechanics once debunked the deterministic view of reality. No matter whether someone finds some utility in the future, the quest for the fundamental laws of physics is intriguing. I hope this essay will pique your curiosity.




**References**

[1] CDF Collaboration *et al.*, "High-precision measurement of the *W* boson mass with the CDF II detector", *Science* **376**, 170-176 (2022).