The Standard Model: He who fights the dragon becomes a dragon himself

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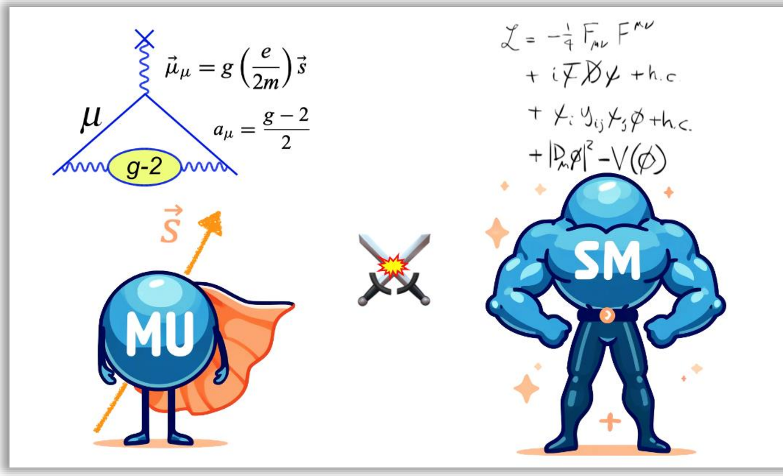

For several hundreds of years, the fundamental motivation that drives physicists forward has never changed: the desire to know how the world works. To answer this question, generations of physicists developed genius theories to explain what has been discovered and predict what has not been discovered yet, and designed state-of-art experiments to test their theory, as well as discover the unknown. Since J. J. Thomson's discovery of the electron, physicists started to realize that all the matter that composes the world is composed of tiny particles at a more elementary level, thus opening the era of particle physics. After that, more particles with different properties were discovered one after another (some of them you may be not familiar with, but no worries): protons, neutrons, leptons, quarks, and anti-particles… all the way to the discovery of the Higgs boson in 2012. In more than a century, each new discovery made the theory describing elementary particles stronger than before, and the discovery of the Higgs boson put the last piece into its place, where the strongest theory model ever in particle physics, or even in physics, the so-called Standard Model,

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comes into being. The Standard Model has successfully explained almost all experimental results and precisely predicted a wide variety of phenomena, established as a well-tested theory and a tremendous milestone in the development of particle physics.

Though achieving unprecedented triumph, physicists firmly believe that this theory is far from perfect. There are many parameters in the model that need to be determined by experiment rather than calculation, and, still, there are some (though not a lot) phenomena that cannot be explained by it. However, as the saying goes: *He who fights the dragon becomes a dragon himself*. Since SM was established, physicists have continuously been engaged in the search for physics beyond the Standard Model, i.e., physics that cannot be explained by the Standard Model, but most efforts turned out to be failures: almost all measurement results were found to agree with the prediction perfectly. I'd like to quote what David Griffith said in the preface of the second version of his book (2008), Introduction to Elementary Particle Physics: *It is 20 years since the first edition of this book was published, and it is both gratifying and distressing to reflect that it remains, for the most part, reasonably up-to-date.* The gratifying side is that every time when the experiment agrees with the Standard Model, it is one more proof of its power, while the distressing side is that, for 20 years (now almost 40 years), there has been no groundbreaking discovery that can lead to an overhaul. The neutrino oscillation is by far the only direct experimental evidence of physics, to which a Nobel Prize was given in 2015.

We've never stopped our efforts to search for the Beyond Standard Model (BSM in following text) because we believe this is not the end of the story. In Switzerland, the world's biggest collider is colliding particles with a speed almost equal to the speed

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of light (>99.999%) 40 million times per second, generating a huge amount of data and finding any tiny but convincing clues of BSM. The Standard Model is, to some extent, an approximation theory at low energy, and it is widely believed that by increasing the energy and amount of data, BSM evidence will appear sooner or later. With this strong belief, while dedicated to improving data analysis with the latest AI techniques, the upgrade for more data is also under preparation and will start from 2025 to 2029. Besides the rising energy level and statistics, there is another way to search for BSM, which is to measure a physics quantity at an extremely precise level and try to find whether there is any discrepancy between the measurement result and theoretical calculation. In particle physics, the former is named the Energy Frontier, and the latter is the Precision Frontier. The idea of the precision frontier is rather simple: how would you prove that a ping-pong ball is not perfectly round? The answer from the precision frontier is that you can zoom in repeatedly and check whether this ball is still round until you find some deflections on the surface. For a ping-pong ball, you're likely to find tiny bumps everywhere on the surface after magnifying 10 times; for SM, physicists have already measured some quantities as precise as parts per billion, which is finding bumps with the size of a cherry on a ball as large as Earth!

At the precision frontier, several experiments are ongoing in parallel. Amongst the most promising of these experiments is the measurement of the anomalous magnetic moment of the muon, known as the muon g-2. Perhaps you are not familiar with what muons are, in fact, every second, more than ten muons actually pass through your body and you've never recognized that! Due to its abundance in cosmic rays, it was the first particle discovered after electron, proton and neutron. However, since it will decay into an electron soon (around 2.2us), until now we still know little about the particle itself, which, on the other hand, will be a sensitive probe to new physics. The magnetic moment is a basic property of muon, which describes the strength of the

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muon reacting to the magnetic field. Its first measurement was from Brookhaven National Laboratory in 2001, and a 3.7 sigma (standard deviation) discrepancy was found between the measurement result and theoretical calculation. With this preliminary result, physicists at Fermilab continued to improve the level of precision. The latest result released last August suggested a 5.1 sigma discrepancy, which is usually recognized as evidence of new physics. 5 sigma means there is less than 0.00006% probability that statistics fluctuation causes a fake signal. However, recent updates from the theory side (I won't go deeper here) are making the theoretical calculation closer to the measurement result. Therefore, the muon g-2 is, at the moment, rather a puzzle than a new piece of physics evidence. Some doubt that the result from Brookhaven and Fermilab is not independent and, in fact, they do share the same magnet, which could possibly be the reason. Therefore besides resolving the theoretical ambiguity, an independent measurement of the muon g-2 is essential. Here in Japan, another experiment aiming at measuring it completely independently is under construction, and data-taking will start in 2028. This is by far the world's only experiment that can provide an independent measurement using different techniques, and the world is waiting for its data and results.

In the next few years before starting operation, the experiment will have a series of upgrades with various physics and technical challenges to overcome. As a member of this experiment collaboration, I'm motivated to make my own contributions to push the precision frontier forward a little bit with my own effort and collaboration with colleagues. Simply enough, this is exactly the reason why I chose to become a scientist. During my high school times, I aspired to be someone driven by curiosity from the bottom of the heart and also pushing the knowledge boundary of humans. Therefore, with an interest in natural science and the dream of understanding the world better, when I entered university I chose to pursue physics, in which I could use

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my own abilities and intelligence to explore the unknown and help humanity gain a better understanding of the world rather than just focusing on earning enough money to enjoy life. Particle physics, which studies the basic components of our world, is the foundation of the whole world, just like cells in the human body. Once we get a better understanding of the particle, we are one more step closer to ‘the theory of everything’. Making contributions to this, for me, is the true essence of leading a meaningful life.

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