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POSSIBLE CLUES ON NEW PHYSICS IN MUON BEHAVIOUR

Interview with Graziano Venanzoni, INFN researcher at the Pisa division, and co-spokesperson for the Muon g-2 collaboration

Last April 7, media from all over the world reported on the first highly anticipated results obtained by Muon g-2, the experiment hosted in the main US particle physics laboratory, Fermilab, dedicated to precisely measuring the anomalous magnetic moment of the muon, a heavy cousin of the electron. The analysis of the first data acquired by the experiment, carried out by the international collaboration responsible for Muon g-2, has provided new evidence for a discrepancy with the predictions of the Standard Model. This model is the imposing theoretical structure that we use today to describe the nature of sub-atomic particles and their behaviour. Despite the fact that it has not yet reached the statistical significance necessary to obtain the status of "discovery", the result could represent an exciting clue as to the presence of phenomena and forces that are yet unknown. If confirmed, the result could also anticipate one of those crucial steps in the history of physics and scientific thought.

Launched in 2017, Muon g-2 has benefitted from an important contribution from INFN. As well as being one of the founders of the experiment, INFN continues to perform a central role within the collaboration through the participation of its Naples, Pisa, Rome 2 and Trieste divisions, of the Udine associated group and of the Frascati National Laboratories. In particular, the Italian researchers have provided an essential contribution both in the implementation and data acquisition phase of the experiment and in the data analysis phase. Further evidence of the centrality of INFN activities is the appointment, in September 2020, of Graziano Venanzoni, INFN researcher at the Pisa division, to the role of cospokesperson for the Muon g-2 collaboration.

Graziano Venanzoni, the Muon g-2 experiment is dedicated to precisely measuring the muon anomalous magnetic moment. Can you please explain to us which muon behaviour this parameter refers to and why it is so important to know its exact value?



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The charged elementary particles that have an intrinsic angular moment called spin, which we can think of as the rotation motion of a spinning top, also possess a magnetic moment, i.e. they produce a magnetic field just the same as a compass needle's. The Standard Model predicts that, for each particle, the value of the magnetic moment is proportional to its spin via a numeric factor that can be calculated and that its value is slightly larger than 2. This factor is usually indicated with the difference between the real value and 2 (g-2). This anomaly associated with the magnetic moment was detected for the first time in the electron at the end of the 1940s by a measurement that was awarded the Nobel prize in 1955. Other increasingly precise experiments succeeded and at the beginning of the 2000s, an experiment with more decisive precision, similar to our own, carried out at the Brookhaven laboratory, near New York, discovered an intriguing discrepancy between the theoretical predictions and the experimental result. A more precise confirmation of this difference with the value predicted by theory can help us to understand if it is owed to the influence exercised on muons by unknown particles. The goal of Muon g-2 is just that of checking this hypothesis by measuring the muon anomalous magnetic moment with four times the precision of that of Brookhaven. If the discrepancy with what is predicted by the Standard Model was to be confirmed, we would, therefore, be facing a discovery of enormous significance that would open the way for new physics.

On April 7, the Muon g-2 collaboration published the first awaited results of the analysis of data collected by the experiment during run 1. What indications did these results provide to the scientific community?

As recorded, the anomaly of the muon magnetic moment has already been known for a long time and is attributed to the quantum fluctuations predicted by the relevant theory, which represents the basis of the Standard Model. Today, we know that all the Standard Model sectors, electromagnetic, weak, and strong, contribute to determining the anomalous magnetic behaviour of the muon. In June 2020, a theoretical collaboration consisting of more than 100 scientists certified the theoretical reference value of the "g-2", achieving a precision of 400 parts per billion. This same collaboration confirmed the discrepancy with the value measured in Brookhaven. The first results published in April have not only shown that our measurement was in excellent agreement with the preceding one, but made it possible to strengthen the significance of the discrepancy from the Standard Model bringing it to 4.2 standard deviations. In other words, by combining the two measurements, we went from a probability of one in 5,000 that Brookhaven's result was owed to a statistical fluctuation to a one in 40,000 probability.



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What does the Muon g-2 equipment consist of and how can it perform such precise measurements of the magnetic properties of the muon?

The heart of the experiment is the accumulation ring, inherited from the Brookhaven laboratory, in which a highly uniform magnetic field enables the circulation of muons for thousands of turns during the measuring time of 700 microseconds. The particles are accelerated at speeds close to that of light and injected with the spin direction aligned with the orbit plane. After this, 24 Cherenkov crystal calorimeters distributed within the ring make it possible to measure the energy and time of the electrons emitted in the muon decay and to reconstruct the spin direction. In addition, two straw tube stations, detectors that use ionised gas and are positioned within the vacuum chamber, make it possible to perform a high-precision "tomography" of the muon beam. Using the precise measurement of the muon spin precession frequency and of the magnetic field (measured with special NMR - nuclear magnetic resonance - probes), we measure the magnetic anomaly of the muon with a precision of 460 parts per billion.

This first success of your collaboration was also a success for Italian physics. What was and what continues to be INFN's contribution to Muon g-2?

INFN made an extremely important contribution that was much appreciated by the Muon g-2 collaboration. First of all, and thanks also to the collaboration with the CNR (National Research Council) National Institute of Optics, we have constructed a laser calibration system that is essential for achieving precision in measuring the anomalous muon spin precession frequency, called ω_a . In addition, we work on many areas of the experiment. We contribute, in fact, to analysing the ω_a measurement, to studying the beam dynamics, to measuring the magnetic field, to acquiring data, and to reconstructing the data themselves using software. These activities are also performed thanks to the contribution of extremely helpful young researchers. Finally, we hold roles of responsibility in many areas of management of the experiment.

You are one of the two spokespersons for the Muon g-2 collaboration. What did you experience when you observed the results for the first time? And what do you hope that the latter might entail for the future of particle physics?

I had opposing feelings. On the one hand, the enormous excitement and emotion in seeing a result so long awaited; on the other hand, I felt the responsibility, as spokesperson of the experiment, to communicate such an important result. The result that we announced relates to 6% of the data that we expect to acquire by the conclusion of the experiment. In the meantime, we have already acquired the data of a second and third research campaign and a fourth is currently underway. Within a couple of years, the data analysis from the second and third campaigns should be ready, which should make it possible to



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reduce the uncertainty by a factor of 2, thus obtaining an even more precise measurement. The hope is that our efforts, together with the results of other experiments that will be performed in the near future at CERN and in Japan, where the measurement of the anomalous moment of the muon is planned using an alternative method, may confirm the discrepancy in relation to the Standard Model predictions and the existence of new physics. Of course, it could happen that, in light of our results, the theoreticians review their prediction, perhaps finding a value closer to the experimental measurement. But this is an integral part of the way in which science progresses, through a continuous and close exchange between experimental measurements and theoretical predictions. I would, finally, like to say something personal: I would like to dedicate this result to Antonio Anastasi, my first student in Muon g-2, an extraordinary young man with great talent who was, unfortunately, unable to witness the completion of his work.