Searching for axions with the ATLAS detector

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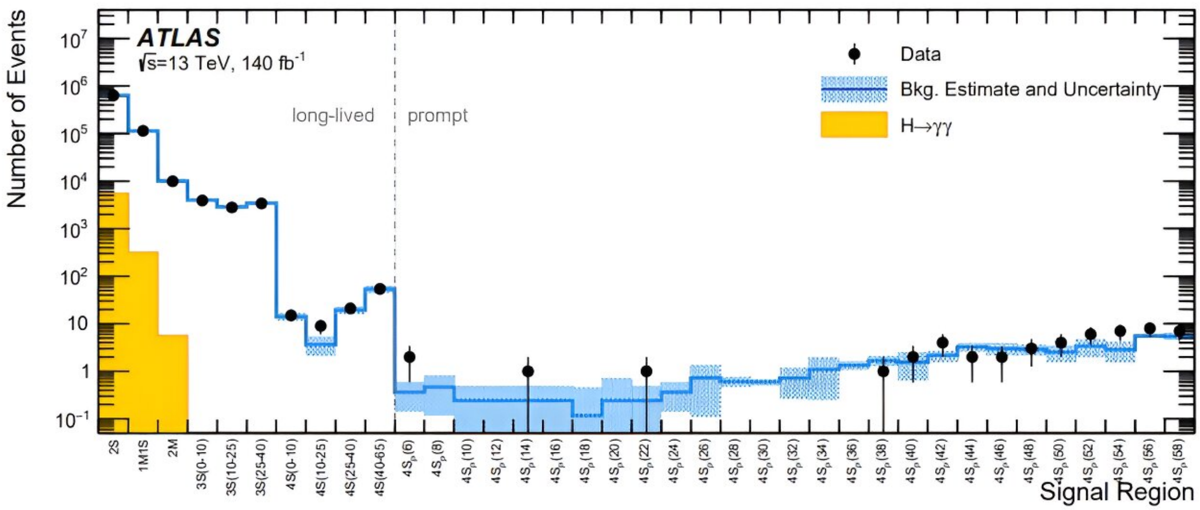

The number of data and estimated background events in the signal region of the most sensitive categories. The uncertainty in the background estimate is shown as shaded band. The left side shows the different categories of the long-lived ALP search, while the right side displays the 4?? category of the prompt search for increasing mass hypotheses. The numbers in parentheses in the x-axis labels correspond to the probed ALP mass hypothesis in GeV. The SM ? → ?? background is only sizeable in the first three bins, corresponding to the two-photon categories. Credit: *arXiv* (2023). DOI: 10.48550/arxiv.2312.03306

The research group of Professor Matthias Schott of the PRISMA+ Cluster of Excellence at Johannes Gutenberg University Mainz (JGU) has posted the results of an extensive series of measurements at the

ATLAS detector of the Large Hadron Collider (LHC) to the *arXiv* preprint server. The data were recorded during the second runtime of the LHC between 2015 and 2018.

The aim of the experimentally challenging measurement program is to search for axion-like particles that could be produced in certain decays of the Higgs particle—and as novel particles could explain the deviation of the experimentally determined anomalous magnetic moment of the muon from its theoretical prediction.

The work represents the experimental test of an axion model developed by Prof. Dr. Matthias Neubert, theoretical physicist and spokesperson of PRISMA+, and is thus an ideal example of the valuable interplay between theory and experiment at the Mainz site.

Axions are hypothetical elementary particles that were initially postulated to solve a theoretical shortcoming of the strong interaction, the so-called strong CP problem. For many years, axions or axion-like particles (ALPs) have also been considered promising candidates for dark matter.

"Against this background, physicists have developed numerous experiments to search for very light ALPs in particular," explains Schott. "For the first time, we have proposed and implemented a detailed research program at the ATLAS experiment of the LHC, with which we specifically search for relatively heavy ALPs—these in turn could explain the puzzle of the anomalous magnetic moment of the muon, as Matthias Neubert showed in a model developed a few years ago."

Together with Martin Bauer and Andrea Thamm, Neubert postulated in 2017 that ATLAS could be used to search a very large range of suitable axion masses with very high sensitivity. For Schott, this was the starting point for the successful application for the ERC grant. "I have now tested a large part of the parameter space of Neubert's model with my group as part of this ERC grant and we are very pleased that we can now publish the first results."

Neubert, for his part, has since clarified the expected effect of ALPs on the muon momentum in a recent article published in the *Journal of High Energy Physics* with Anne Galda.

An innovative experimental achievement

The series of measurements is based on the idea that potential ALPs must couple to both the muon and photons in order to explain the anomaly in the magnetic moment of the muon. Specifically, the researchers investigated a theoretically postulated decay chain in which a Higgs particle first decays into two ALPs, and these in turn into two photons each (H à aa à 4ɣ). The aim was to detect the coupling of the ALPs to the photons in this chain.

"We did not find any conspicuous signals that could indicate corresponding ALPs," explains Schott. "In the investigated area, we can therefore rule out axion-photon coupling with the utmost probability." However, as the research group was able to search a very large parameter range for the first time and was six orders of magnitude more sensitive than previous measurements, particularly with regard to the coupling strength, they have succeeded in setting the strictest exclusion limits to date for the mass and coupling strength of ALPs.

Neubert says, "The special thing about this measurement is that ALPs can potentially be detected via Higgs physics. We are in the high-energy range of particle physics and can thus track down the discrepancy in the anomalous magnetic muon moment via the conversion of high-energy particles. This is a complementary approach to the direct measurement of the properties of the muon in the low-energy range as part of the muon g-2 experiment, which is precisely what makes it so exciting."

New analysis algorithms based on artificial intelligence

The decay process investigated by Schott's group is experimentally very challenging, primarily because the photons to be detected from ALP decay are not produced at the collision point of the detector. "In normal particle collisions, the particles always meet exactly in the middle of the detector. And any new particles that are created in this collision, we typically assume that their journey starts right at the collision point. The normal algorithms and calibrations we have are based precisely on this hypothesis," explains Schott.

"However, if new particles are created that 'live' long enough, then these particles first fly a short distance before they decay. This means that our original assumption no longer applies and we have to develop completely new approaches in order to also see particles in the detector that do not originate from the collision point."

Specifically, in Neubert's model, the Higgs particle first decays into two ALPs immediately at the point of the particle collision. However, the ALPs fly for a while before they each decay into two photons, so that these photons are produced away from the collision point. "We call these events with a displaced vertex—a displaced collision point, so to speak. We have now succeeded in making such a measurement with photons for the first time."

In addition, there is another challenge: if the ALPs are comparatively light, the photons into which they decay are very close together. The detector perceives the two photons as a single photon—unless there is a new algorithm that is trained to do just that: that is, that can recognize photons that were actually reconstructed as one photon as two photons. "We were able to develop such an algorithm using artificial intelligence in the form of neural networks and thus successfully resolve signals from highly collinear photons."

But there is more. Even with the specially developed algorithms, with which the researchers can cover a very large search area, they cannot "catch" all the ALPs they want to target. To close this gap as well, they want to use the FASER experiment, which has now gone into operation in a side tunnel of the LHC around 480 meters behind the ATLAS experiment.

The muon as a test lab for new physics

Just recently, the muon g-2 collaboration at Fermilab announced a new measurement value for the anomalous magnetic moment that is twice as accurate as the previous one. The PRISMA+ working group led by Prof. Dr. Martin Fertl is the only one in Germany that is involved with experimental contributions. The counterpart is the muon g-2 theory initiative, a worldwide association of more than 130 physicists that deals with theoretical predictions within the framework of the standard model.

Here, too, the Mainz working groups of Prof. Dr. Achim Denig, Prof. Dr. Harvey Meyer, Prof. Dr. Marc Vanderhaeghen and Prof. Dr. Hartmut Wittig make numerous important contributions—from the measurement of experimental input variables to the high-precision calculation of the contributions of the strong interaction using the methods of lattice quantum chromodynamics on the Mainz mainframe computer MOGON-II.

Based on the latest calculations, it is still not clear whether there is a genuine discrepancy between theory and experiment and, if there is, which theoretical approaches could be used to explain it. However, it once again demonstrates the great expertise of the PRISMA+ cluster in Mainz in the search for new physics—and here in particular in the interplay between theory and experiment and the use of complementary methods to answer the big questions of modern physics.

"Our work published today is an important contribution here, although it shows that the space for models of new physics that we can test experimentally is getting smaller and smaller," says Schott, categorizing the result. "With regard to ALPs, these are still promising candidates for dark matter, but we can very probably rule them out as the cause of a discrepancy in the magnetic moment of the muon."

More information: Search for short- and long-lived axion-like particles in $H \rightarrow aa \rightarrow 4\gamma$ decays with the ATLAS experiment at the LHC, *arXiv* (2023). DOI: 10.48550/arxiv.2312.03306

Anne Mareike Galda et al, ALP-LEFT Interference and the Muon (g − 2), *Journal of High Energy Physics* (2023). DOI: 10.1007/JHEP11(2023)015. On *arXiv*: DOI: 10.48550/arxiv.2308.01338

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