Higgs Decays as an Explanation for the Anomalous Muon Magnetic Dipole Moment

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This paper addresses the anomalous muon magnetic dipole moment as a long-standing deviation of experiment from the Standard Model of particle physics and introduces pseudoscalar mediators in Higgs boson decays as a possible explanation. Pseudoscalar mediators are motivated by certain Beyond the Standard Model (BSM) theories that address topics including dark matter studies and the baryon asymmetry problem, thus also offering a solution to the naturalness problem. Visualized data is taken from the Hbb$\mu\mu$ group of the ATLAS collaboration, from analyses of decays H → aa → bb$\mu\mu$ and H → Za → bb$\mu\mu$.

I. INTRODUCTION

The Standard Model of particle physics, often referred to as "the most successful scientific theory," is a framework that describes matter and energy at the most fundamental level. It describes how the basic building blocks of the universe interact through three fundamental forces. Within the Standard Model lies the Higgs boson, which gives rise to the mass-giving Higgs field. This boson is unstable and known to decay into a number of final states, and these various decays are studied to better understand the fundamental particles and how they interact.

Some extensions of the Standard Model hypothesize light-like pseudoscalars, which couple to the mass of the Higgs boson and are proposed as an explanation for the anomalous muon magnetic dipole moment. The magnetic moment measures the strength of a magnetic source; for the magnetic moment of the muon, there exists a significant difference between experimental measurement and what the Standard Model predicts. This is called the anomalous muon magnetic dipole moment and has been a long-standing deviation between experiment and theory. Muon g-2 is an experiment designed to measure the anomalous muon magnetic dipole moment and effectively acts as a test of the Standard Model. It was first conducted at CERN, then at Brookhaven National Laboratory (BNL), and now at Fermilab [Aguillard, 2024].

Here we focus on the decay H → aa → bb$\mu\mu$, in which the Higgs boson decays into two such hypothetical pseudoscalars 'a', one of which then decays into a b-quark pair and the other into a dimuon pair. Through analysis of this decay, we look to see if the couplings and masses of these pseudoscalars exist within a certain range. If so, then they may enhance the magnetic dipole moment by their loop effects, thus explaining the excess that is observed experimentally. In addition to this phenomenon, these pseudoscalar particles also appear in models relating to the nature of dark matter and even address the baryon asymmetry problem.

If this discrepancy is indeed due to such a new pseudoscalar particle, this would be confirmation of physics beyond the Standard Model which has far-reaching implications for new physics. The deviation may inform Grand Unified Theories (GUTs), which merge the electromagnetic, strong, and weak forces. Many supersymmetric models also predict corrections to the muon magnetic moment, so a resolution to this anomaly may confirm or constrain such models and thus be used to test supersymmetry. As such, an explanation for the anomaly would act as a test of the Standard Model and potentially guide scientists to a more comprehensive theory of fundamental particles and forces beyond it.

II. HISTORY AND BACKGROUND

To understand Higgs decays, I first introduce the Standard Model of particle physics which describes the elementary matter particles and forces by which they interact.

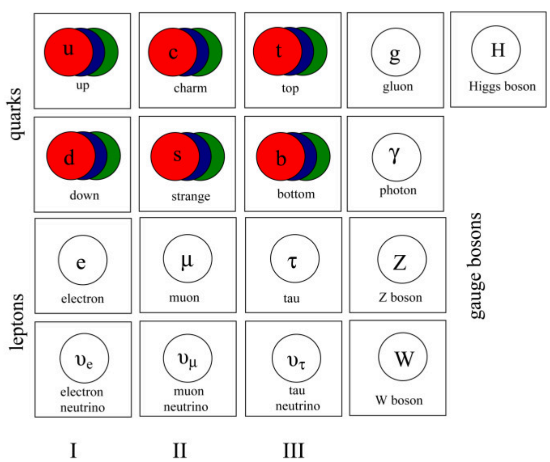


Figure I. Standard Model of Particle Physics

Matter particles are called fermions, and they obey Fermi-Dirac statistics and have half-integer spin. Fermions are shown in the first three columns of Figure I and include quarks and leptons. Quarks are matter particles that interact via the strong and electroweak interactions. Groups of three quarks form protons and neutrons, which combine with electrons to make the atoms that everyday matter is made from. The remaining fermions are called leptons, and they interact only via the electroweak interaction. These include electrons and electron neutrinos, as well as their heavier generations of the muon and tau varieties. It should be noted that all of the fermions appear in three generations, distinguished only by mass. That is, the particles in each row of fermions in Figure I (from the first three columns) have the same charge and spin, but increase in mass from left to right.

Next, the force-carrying particles are called gauge bosons, and they obey Bose-Einstein statistics and have integer spin. Each gauge boson is tied to a fundamental force. The photon is responsible for the electromagnetic force, the gluon for the strong force, and the W and Z bosons for the weak force.

Finally, we have the Higgs boson – the only scalar boson with spin zero, and the basis of this paper. According to symmetry requirements, the weak force gauge bosons (W and Z bosons) should be massless. However, experiments showed that they are indeed massive, and so the Higgs field was conceived to explain their mass through a symmetry-breaking mechanism. This field suggested a new particle, the Higgs boson, which would give rise to this Higgs field. Upon interaction with the Higgs field, the W and Z bosons acquire a rest mass and in addition to the mechanism of Yukawa coupling, so do quarks and leptons. In essence, the Higgs field permeates our universe and when elementary particles interact with it, they acquire a rest mass; the stronger this interaction, the more mass they acquire. The Higgs boson responsible for this field was experimentally verified in 2012 and was the final discovery that completed the Standard Model.

The Higgs boson is extremely unstable and decays into other Standard Model particles upon generation. Elementary particle decays can be characterized as either hadronic or leptonic, which are distinguished by their final states and branching ratios. The branching ratio measures the likelihood of a particle decaying into a particular final state compared to all possible decays. Hadronic decays are those into hadrons, which are groupings of quarks. These decays are governed by the strong interaction and have larger branching ratios due to the great variety of quark flavors. On the other hand, leptonic decays are those into electrons, muons, and taus. These decays correspond to the weak interaction and have smaller branching ratios.

Common Higgs decays include those into heavier quarks, W and Z bosons, and photons. These are well-understood and used as a baseline to which we compare more exotic ones. Rarer decay modes would be Higgs to pseudoscalars and less massive leptons like muons and electrons, and these are a current focus of particle physics research because they are predicted to uncover new physics. The topic of this paper is pseudoscalar mediators, and more specifically the decay of $pp \rightarrow H \rightarrow aa \rightarrow bb\mu\mu$.

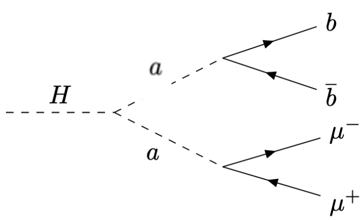


Figure II. $H \rightarrow aa \rightarrow bb\mu\mu$

This illustrates a Higgs boson produced from a proton-proton collision, which decays into a pair of pseudoscalar 'a' bosons. One of these decays into a b-quark pair ($a \rightarrow bb$), and the other into a dimuon pair ($a \rightarrow \mu\mu$).

Certain BSM theories tell us that the loop effects of such pseudoscalar mediators may contribute to the observed excess in the magnetic dipole moment of the muon [Yu, 2022]. This discrepancy, often referred to as $(g–2)_\mu$, has been measured to disagree with Standard Model predictions by 3.5 standard deviations as of 2017 [Davier, 2017]. This measurement was made using electron-positron cross section data from the BaBar experiment, however newer results are being published from different experiments with slightly lower deviations. Currently, the Muon g–2 experiment to measure the discrepancy is being conducted at Fermilab, where the anomalous muon magnetic moment has been measured to a much greater accuracy than previous measurements from CERN and BNL. These improving measurements combined with emerging theories for pseudoscalar mediators as a contribution to the excess in magnetic dipole moment for the muon may be enough to solve the $(g–2)_\mu$ problem.

III. MATHEMATICAL FORMULATION

For a particle such as the muon, the magnetic moment is related to its spin by the equation

$$\mu = g\frac{q}{2m}S$$

where q is charge, m is mass, S is spin, and g is the gyromagnetic ratio. This is defined as the ratio of the muon's magnetic moment to its angular momentum.

The anomalous magnetic moment of the muon is then given by the equation

$$a_\mu = \frac{g_\mu - 2}{2}$$

Muons interact with quantum fields, and this causes deviations from $g = 2$. Therefore, the actual g_μ factor is given by $g_\mu = 2 + \Delta g_\mu$. This is where we get that $\Delta g_\mu = g_\mu - 2$. The anomalous dipole moment is related to the deviation from the gyromagnetic ratio (Δg_μ) by a factor of one half in the "ideal case" and thus, we get that $a_\mu = \frac{\Delta g_\mu}{2} = \frac{g_\mu - 2}{2}$.

The Standard Model prediction of the value of a_μ is given by the formula

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{hadron}$$

where combined values are as follows:

a_μ^{QED} = quantum electrodynamic (QED) contributions from photonic and leptonic loops

a_μ^{EW} = electroweak (EW) contributions from W and Z-boson loops

a_μ^{hadron} = contributions from hadronic vacuum polarization

From this equation, a_μ^{QED} and a_μ^{EW} are calculated from first principles, but a_μ^{hadron} cannot be deduced this way. It must rather be estimated experimentally, typically from the ratio of muon cross-sections in electron–positron collisions. The issue arises here because experimentally observed values of a_μ significantly disagree with what the Standard Model predicts with a discrepancy of around 3.5 standard deviations. The Standard Model returns a value of $a_\mu = 0.00116591805 \pm 0.00000000051$, and the world average is $0.00116592059 \pm 0.00000000022$ [Hoferichter, 2022].

IV. ATLAS DETECTOR

Higgs bosons are produced in proton-proton collisions at extremely high energies. These energies are achieved by particle accelerators like the Large Hadron Collider (LHC) at CERN. The LHC is the largest and most powerful particle accelerator in the world and lies underground on the French-Swiss border at roughly 8.5 kilometers in diameter.

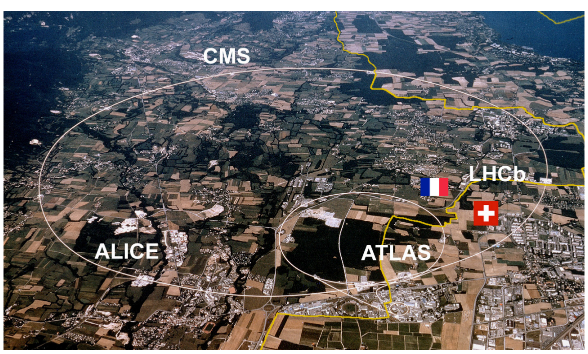


Figure III. Large Hadron Collider Map [Cosmol, 2023]

Within the collider, beams of protons are accelerated to high energies and then made to collide at various points along its path. Once produced in a proton-proton collision, the Higgs boson quickly decays into other Standard Model particles, which are detected by the particle detectors inside the accelerator. The data provided in this paper is taken from the ATLAS detector.

Only one in roughly one billion collisions produces a Higgs boson, so massive amounts of data must be collected to properly study the particle. In order to study specific decays, especially the exotic ones with low branching ratios like the leptonic decay in our H → aa → bb$\mu\mu$, we require incredible amounts of data. As such, the data presented in this paper is taken from LHC Run 2, which ran from 2015 to 2018 at a proton-proton collision energy of 13 TeV (almost double of Run 1 which ran at 8 TeV), and collected approximately 140 fb^{-1} of data. That is, approximately 140 collisions per femtobarn of the proton beam's cross-sectional area were collected in Run 2 of the LHC. Currently, the LHC is on its third run which began in April 2022 and will end in 2026. It has achieved a record energy of 13.6 TeV.

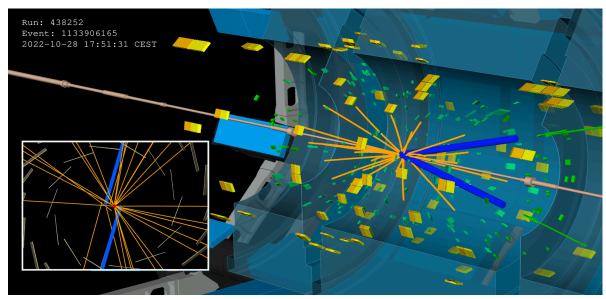


Figure IV. Highest-ever collision energy of 13.6 TeV [ATLAS Collaboration, 2023]

V. OBSERVATION AND RESULTS

Confirmation of the pseudoscalars 'a' being responsible for the $(g-2)_\mu$ discrepancy requires careful analysis of the H → aa → bb$\mu\mu$ decay. In such an analysis, we evaluate the signal of interest (the bb$\mu\mu$ decay) against its backgrounds and create a number of plots for different parameters, like mass, momentum, number of jets, etc. In the acceleration, proton-proton collisions produce a number of processes with various decay channels. Many of these decays have different final states, but some of them are the same. While the decay processes are different, they achieve the same final state.

These processes that mimic the final state of our signal are called “backgrounds”. For the H → aa → bb$\mu\mu$ decay, the dominant backgrounds are Z+ jets, also called Drell-Yan, and ttbar ($t\bar{t}$).

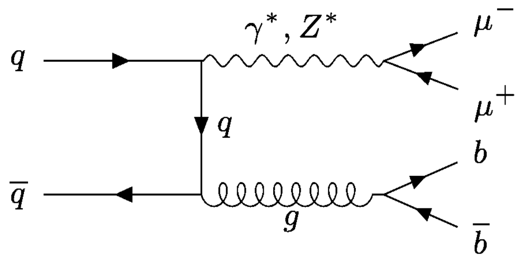


Figure V. Drell-Yan Process

In the Drell-Yan background, a quark-antiquark pair decays into a Z-boson or a virtual photon and a gluon. The Z-boson/photon then decays into a dimuon pair and the gluon into a b-quark pair. This background has exactly the same final state as our signal with the b-quark pair from the hadronic decay and the dimuon pair from the leptonic decay. That means that this decay is particularly difficult to distinguish from the signal, not just because of its dominance as an abundant background, but also because it perfectly copies the decay that we are trying to isolate and study.

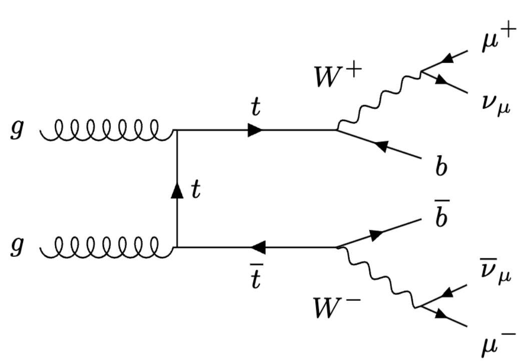


Figure VI. ttbar Process

The ttbar process illustrates top-antitop pair production, with each decaying into a W-boson and a bottom quark (top decaying into W^+ and b-quark and antitop decaying into W^- and antibottom quark). The final state of this background differs slightly from that of the signal because of the additional neutrinos that appear, but it is nevertheless a dominant background due to its sheer quantity in detection.

Analyses of Higgs decays are performed using machine learning programs that take in data from the detectors within the particle colliders and run through all of the events, filtering out those that are not of interest. The program can quickly filter out processes that produce different final states, but for the backgrounds of the signal, it works in “cuts”. At each cut, a different requirement is placed on the events such that those allowed will go through to the next cut while the rest will be excluded from the analysis. For example, the Drell-Yan background is greatly reduced by placing the requirement that the dimuon mass be between 10 and 65 GeV; that is $10 < m_{\mu\mu} < 65$ GeV. Other selections within this analysis include that there be exactly two muons ($N_\mu = 2$), that the muons be of opposite signs (OS), and that the transverse momentum of the b-jets be greater than 20 GeV ($p_T^b > 20$ GeV). The significant restrictions, called event selections, on H → aa → bb$\mu\mu$ events for signal isolation are given in figure VII.

Trigger	Unprescaled single or dilepton trigger match	
Muons	$N_\mu = 2$ Opposite Sign (OS) $10 < m_{\mu\mu} < 65$ GeV	
***b*-jets**	$p_T^b > 20$ GeV $N_b = 2$	
Likelihood: $\ln(L^{\max})$	> -8	
Region	Signal Region	Top Control Region
E_T^{miss} (GeV)	< 60	> 60

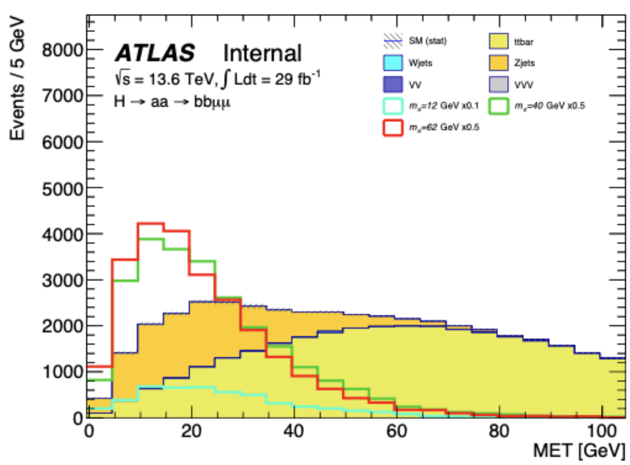
Figure VII. Event Selection [SBU ATLAS Hbb$\mu\mu$ Group*]*

At each cut, the program compiles a number of plots for parameters like mass, momentum, jet number, transverse energy, and more. The important detail in these plots is that the program distinguishes between the signal and backgrounds so that we can see improvements in our plots incrementally as we place more and more restrictions on the events. The number of signal and background events that pass through the program at each cut are visualized in a cutflow. Figure VII is an example of such a cutflow from a $H \rightarrow Za \rightarrow bb\mu\mu$ analysis.

$\sqrt{s}$=13.6 TeV, L=29 fb^{-1} μμ(2022)	m_a=18 GeV	m_a=25 GeV	m_a=30 GeV	ttbar	Z+ jets
Base cut	47.83 ± 0.25	66.21 ± 0.29	81.45 ± 0.32	50229.25 ± 58.49	11272.15 ± 105.48
Single OR Dilepton Trigger Match	23.52 ± 0.17	29.27 ± 0.19	42.98 ± 0.23	47585.02 ± 56.93	12718.06 ± 87.27
$N_\mu = 2$	22.71 ± 0.17	28.17 ± 0.19	41.73 ± 0.23	47410.63 ± 56.82	12659.28 ± 86.87
OS Muons	22.36 ± 0.17	27.89 ± 0.19	41.57 ± 0.23	46758.69 ± 56.43	12578.88 ± 86.63
Muons η<2.47	22.24 ± 0.17	27.77 ± 0.19	41.38 ± 0.23	46582.58 ± 56.32	12507.77 ± 86.42
Muons Isolation Loose_VarRad	18.43 ± 0.15	22.68 ± 0.17	34.32 ± 0.21	42491.73 ± 53.79	10859.25 ± 81.61
$N_b == 2$ & $p_T{}^b >= 20$ GeV	5.51 ± 0.08	6.93 ± 0.09	10.44 ± 0.11	40298.40 ± 52.38	10479.21 ± 81.00
$10 < m_{\mu\mu} < 65$ GeV	5.51 ± 0.08	6.93 ± 0.09	10.44 ± 0.11	36196.17 ± 49.64	9774.91 ± 78.14
$E_T{}^{miss} < 60$ GeV	5.26 ± 0.08	6.63 ± 0.09	10.07 ± 0.11	14019.59 ± 30.89	9244.27 ± 77.23
Likelihood > -8	0.01 ± 0.00	0.04 ± 0.01	0.20 ± 0.02	1430.03 ± 9.86	1331.35 ± 33.48
VR: Likelihood ≤ -8	5.25 ± 0.08	6.59 ± 0.09	9.87 ± 0.11	12589.49 ± 29.27	7913.15 ± 69.59
$E_T{}^{miss} > 60$ GeV	0.25 ± 0.02	0.31 ± 0.02	0.37 ± 0.02	22176.59 ± 38.86	530.65 ± 11.93
Likelihood > -8	0.00 ± 0.00	0.00 ± 0.00	0.01 ± 0.00	2234.98 ± 12.32	63.74 ± 5.14

Figure VII. $H \rightarrow Za \rightarrow bb\mu\mu$ Cutflow [SBU ATLAS Hbb$\mu\mu$ Group] (This cutflow is actually taken from my own research with Stony Brook's ATLAS group!)

Ideally, the signal would remain high while the background consistently decreases, effectively isolating the signal. However, this rarely is the case as we tend to lose some signal to the restrictions that are meant to mitigate the backgrounds. For example, Figure VII depicts a plot for the



missing transverse energy (MET) for $H \rightarrow aa \rightarrow bb\mu\mu$ taken at the cut that requires that there be exactly two b-jets; that is $N_b = 2$.

Figure VIII. MET at 2 b-jet Cut

VI. APPLICATIONS TO NEW PHYSICS

The anomalous muon magnetic dipole moment is a test of the accuracy of the Standard Model. The significant 3.5 standard deviation difference between theory and experiment suggests that the Standard Model is incomplete and that there is something new at hand making these contributions to the magnetic moment of the muon. While pseudoscalar mediators are the topic of this paper as a possible solution, this excess may also be the result of contributions by supersymmetric particles, dark matter particles, or other new particles predicted by theories Beyond the Standard Model.

If such a new particle does exist, then this would imply a much richer particle spectrum than the one that the Standard Model currently describes. This is particularly exciting because of the current, intense efforts to probe dark matter and understand the baryon asymmetry (matter-antimatter asymmetry) problem. A broader scale of matter and energy particles may lead us to an explanation for these other mysteries in physics! The pseudoscalar 'a', in particular, is thought to be a mediator that connects the Standard Model to the dark sector. Additionally, it may act as a light pseudoscalar for a two-Higgs doublet model (2HDM) or its supersymmetric extension. On the other hand it could also be an axion-like particle, which is a QCD axion generalization that appears in many physical frameworks including that of string theory. Pseudoscalar particles have possible connections to so many exciting ventures in new physics.

VII. CONCLUSION

The magnetic moment of the muon has long been a test of the Standard Model, the results of which are yet to be settled. The great difference between predictions from the Standard Model, an incredibly successful theory that has stood the test of time, and experimental observation suggests new physics. Theories Beyond the Standard Model address burning questions in physics, like the nature of dark matter, the imbalance of matter and antimatter in our universe, supersymmetry, and more. Confirmation of just one particle outside of the Standard Model will open doors to a wealth of new physics regarding these topics.

In these efforts to solve the $(g-2)_\mu$ problem, scientists are making advances to instrumentation and technology, further testing and verifying existing theories, and pushing the frontiers of science to new and exciting places.

References

Aguillard, D. P., Albahri, T., Allspach, D., Anisenkov, A., Badgley, K., Baeßler, S., Bailey, I., Bailey, L., Baranov, V. A., Barlas-Yucel, E., Barrett, T., Barzi, E., Bedeschi, F., Berz, M., Bhattacharya, M., Binney, H. P., Bloom, P., Bono, J., Bottalico, E., … Zhang, C. (2024). Detailed report on the measurement of the positive muon anomalous magnetic moment to 0.20 PPM. *Physical Review D*, *110*(3). https://doi.org/10.1103/physrevd.110.032009

Davier, M., Hoecker, A., Malaescu, B., & Zhang, Z. (2011). Reevaluation of the hadronic contributions to the muon g−2 and to $\alpha (m^{2}_{z})$. *The European Physical Journal C*, *71*(1). https://doi.org/10.1140/epjc/s10052-010-1515-z

Davier, M., Hoecker, A., Malaescu, B., & Zhang, Z. (2017). Reevaluation of the hadronic vacuum polarisation contributions to the standard model predictions of the muon $$g-2$$ G - 2 and $${\alpha (m_z^2)}$$ α (M Z 2) using newest hadronic cross-section data. *The European Physical Journal C*, *77*(12). https://doi.org/10.1140/epjc/s10052-017-5161-6

Yu, B., & Zhou, S. (2022). General remarks on the one-loop contributions to the muon anomalous magnetic moment. *Nuclear Physics B*, *975*, 115674. https://doi.org/10.1016/j.nuclphysb.2022.115674

Hoferichter, M. (2022). *The Anomalous Magnetic Moment of the Muon in the Standard Model*. https://doi.org/10.52843/cassyni.q2rr53

ATLAS Collaboration. (2023, May 24). *ATLAS measures the Higgs boson at 13.6 TeV*. ATLAS Experiment. https://atlas.cern/Updates/Briefing/Run3-Higgs

Comsol. (2023, March 29). *Analyzing the LHC magnet quenches*. IEEE Spectrum. https://spectrum.ieee.org/analyzing-the-lhc-magnet-quenches