Title: Navigating Anomalies in the Pursuit of New Physics

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Article summary and Program Acknowledgement:

In this article, I explore the pursuit of new physics through particle physics, aiming to unravel some of the mysteries of the universe. As an Experimental Particle Physicist, I share my journey and collaborative efforts in uncovering the fundamental building blocks of nature. The article shares how, through the ATLAS Experiment at CERN, my colleagues and I delve into particle physics boundaries, using innovative anomaly detection techniques driven by artificial intelligence and machine learning to pinpoint anomalies that could lead to groundbreaking discoveries. Using some results from our recent publication, the article highlights the advancements in anomaly detection methods, showcasing their potential to increase sensitivity to new physics phenomena and drive future breakthroughs in our understanding of the universe.

I am pleased to contribute to the program "Sharing UW-Madison Postdoctoral Scholarly Research with Non-Science Audiences," sponsored by the Wisconsin Initiative for Science Literacy (WISL). This program, made possible by the dedication of the WISL staff, specifically Cayce Osborne, Elizabeth Reynolds, and Professor Bassam Shakhashiri, plays a crucial role in fostering connections between scientific exploration and a wider audience. As a postdoctoral researcher, my journey is not limited to research alone. It comes with an important responsibility to share the wonders and experiences of scientific research with diverse communities.

Navigating Anomalies in the Pursuit of New Physics

Dr. Wasikul Islam

Have you ever gazed at the twinkling stars in the night sky, pondering their mysteries and composition? Or observed natural phenomena, seeking to understand their dynamics? If so, you possess curiosity—the driving force behind all scientific inquiries. In particle physics, we delve into the fundamental building blocks of the universe, exploring the complex behaviors of subatomic particles that shape what we observe around us. Join me on this journey as I narrate my recent works in particle physics to unravel some of the mysteries of the sub-atomic world.

My Personal Quest:

I am an Experimental Particle Physicist from the University of Wisconsin-Madison, and along with many other Physicist colleagues from our Wisconsin Physics Department, I work at the ATLAS Experiment at the European Organization for Nuclear Research (CERN) laboratory in Switzerland. I spend my days searching for hidden treasures –unknown new physics – using a giant machine called the Large Hadron Collider (LHC), which smashes particles together at incredible speeds. I collaborate with thousands of physicists from around the globe to run our gigantic experiment with the goal of understanding some of the deepest secrets of our universe.

My journey started many years ago in my small hometown Beldanga, in India, where my fascination and love for the stars in the night sky led me to study physics, as only physics could give me more information about those fascinating celestial wonders. As I pursued physics studies further, uncovering the components and dynamics of stars, I discovered that their fundamental building blocks are identical to those comprising our planet, its landscapes, and even ourselves as human beings. This realization fueled my desire to dive deeper into the study of these fundamental building blocks, ultimately leading me to a career in particle physics research.

Fundamental Particles, the building blocks:

In our field of particle physics, we view our universe through the lens of a scientific framework named the Standard Model of Particle Physics. In this model, all the phenomena in nature can be explained by 4 fundamental interactions, and tiny subatomic particles act as building blocks for almost everything around us.

According to our latest understanding, there are 17 types of fundamental subatomic particles, which are the keys to matter and the interactions in nature. Among these, particles like quarks and leptons constitute what we call "matter particles," forming all known objects in our visible universe. Additionally, particles like gluons, W bosons, and Z bosons, known as "force-carrying particles", mediate the fundamental forces of nature. The latest addition to this list is the Higgs boson, responsible for providing mass to other fundamental particles. It's worth noting that many physicists from Wisconsin, working on the ATLAS and CMS experiments at the CERN laboratory, played a significant role in the discovery of the Higgs boson in 2012, a breakthrough hailed as one of humanity's greatest scientific achievements. And here is another fascinating fact - my postdoctoral advisor and Wisconsin Physicist Prof. Sau Lan Wu participated in the discoveries of 3 of those 17 fundamental particles: the charm Quark, Gluon & the Higgs boson!

The Quest for New Physics:

The term ‘new physics’ symbolizes new explorations and curiosity beyond what is already known to us through centuries of investigation. New physics may appear to scientists both as an extremely tiny discrepancy in the established physics ideas or as fresh physics ideas about our universe that reveal unchartered territories of knowledge. It is like inspecting the walls of your familiar house and noticing minor cracks or irregularities, indicating discrepancies in the established structure, or discovering an unexpected passage hiding in your basement, leading to the revelation of a vast underground palace full of treasures. You may wonder why physicists should be bothered to search for new physics. The answer lies in the limitations of our current knowledge. When we look at our universe from the lens of the Standard Model of particle physics, we can only see 4% of our universe. The remaining 96% is veiled in darkness, we don’t know about any of the physical laws that govern over there. We still don’t know much about dark matter and dark energy, which many researchers propose to account for 96% of our universe, which remains unexplored and full of mysteries.

New physics ideas can also fill gaps in our understanding by finding answers to unsolved questions about already discovered particles. For example, we know how the Higgs boson interacts with some of the fundamental particles, but we don’t know whether the Higgs boson interacts with itself. Such information on the possible self-interaction of the Higgs boson could improve our understanding of the very early phase of our universe and beyond. So for physicists trying to understand the universe by studying its puzzles, searching for new physics is unavoidable.

The ATLAS Experiment: Our Giant Detective:

The ATLAS Experiment at CERN, also known as A Toroidal LHC Apparatus, has already racked up many achievements, including the Nobel Prize-winning (2013 Physics Prize) discovery of the Higgs boson (Higgs boson was co-discovered with another Experiment at CERN, the CMS Experiment) so far. It continues to work as a successful giant detective for solving the puzzles of particle physics by studying the properties of tiny particles, performing complicated measurements, and searching for new physics beyond the Standard Model. It sits

100 meters underground at one of the collision points of a 27 km long gigantic circular underground tunnel of the Large Hadron Collider (LHC). With significant contributions from Wisconsin physicists, ATLAS operates as the largest particle detector ever constructed. It weighs a staggering 7000 tons, similar to the weight of the iconic Eiffel Tower! The experimental detector is 46 meters long, 25 meters high, and 25 meters wide, and is composed of many layers of sub-detectors. Each of these sub-detectors specializes in identifying the properties of different sets of particles coming out from the collision points. The following iconic picture (fig 1) of a section of the ATLAS detector with a Physicist (Dr. Roger Ruber) may give an idea of the size of the gigantic detector.

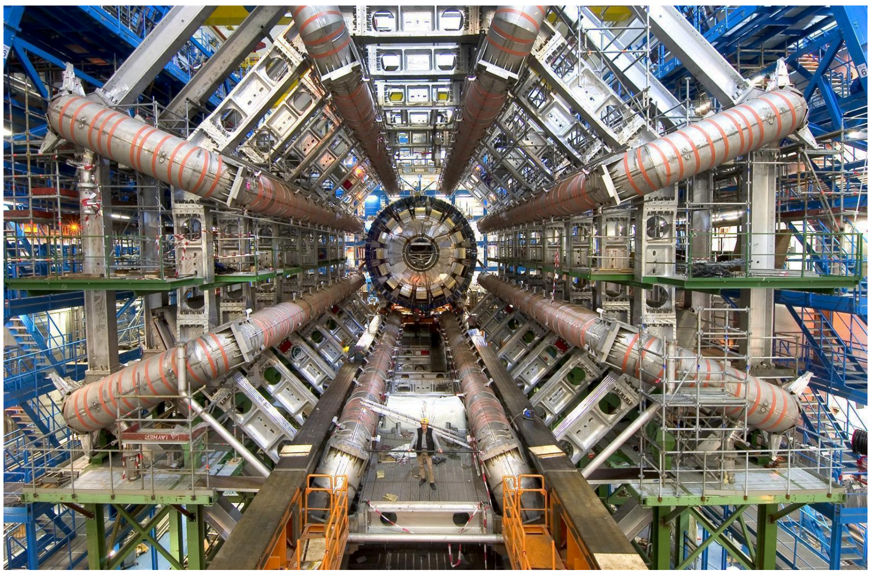
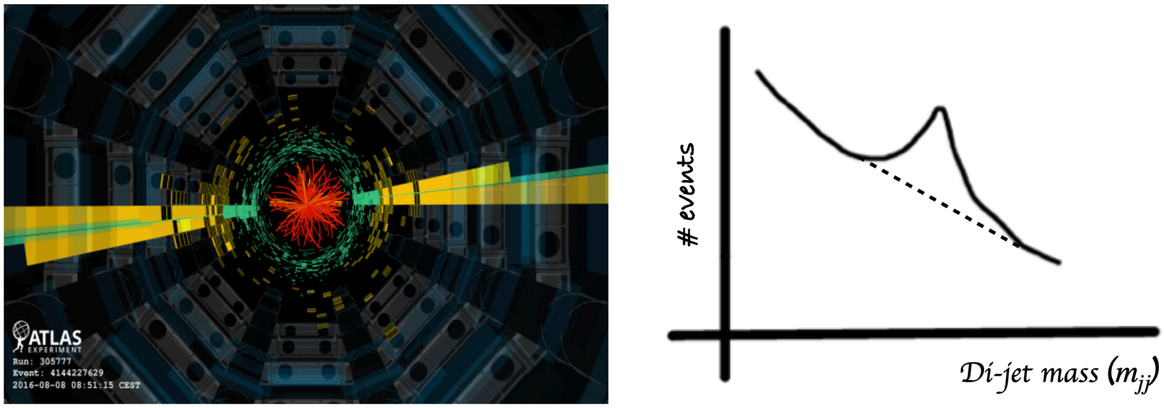


Fig 1: An iconic picture of a physicist with the ATLAS detector at CERN

What makes the LHC special is that it operates at the highest energy ever reached by our human civilization, and it continues to push the boundaries in the energy frontier. Currently, we collect data on particle collisions at 13600 Giga Electron Volts (GeV), which has been unprecedented in history. To explain more about this unit, a Giga Electron Volt is a billion times more than an electron volt (eV). For example, a very low-energy X-ray can have an energy of around 100 (eV). Now, multiply that by an astounding 136 billion times to comprehend the colossal energy scale of 13600 GeV. Conducting experiments at such high energies provides us with a broader scope to look for new particles with high masses and new physics interactions at these high energies.

Our recent strategies to search for New Physics:

In my pursuit of new physics, while using data produced at the ATLAS experiment, I have used various techniques to search for new particles and new physics processes that could help us discover Dark matter and hypothetical particles, such as the Charged Higgs boson or W prime boson. A common approach in my multiple works was searching for new physics in di-jet resonances.



(a) (b)

Fig 2: (a) An Event display of a Di-jet event from ATLAS data, recorded in 2016. Two jets, coming out from the collision point in opposite directions can be seen in yellow color [Ref.: https://cds.cern.ch/record/2669151] (b) Demonstration of a Di-jet resonance above observable spectra.

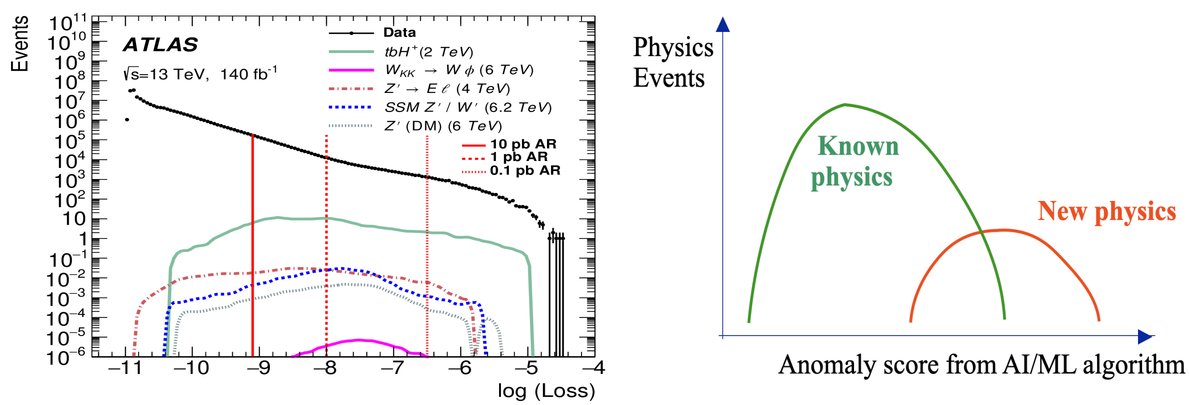
A jet is a shower of particles coming out of a collision. When two such jets come out from a collision event, we call it a di-jet event (see an example in Fig 2a). I have been searching for new phenomena, which results in 2 jets, produced during particle collisions, and manifest as a narrow resonance peak above the observable spectra (see demonstration in Fig 2b). Such resonances (peaks located around certain energies), if not predicted by the standard model, can serve as potential signals for new physics—such as dark matter, other exotic particles, or entirely novel phenomena that were previously unknown to us. To uncover whether such resonances hide within the experimental data, we have embraced an innovative approach—using an Anomaly detection technique on the ATLAS Experiment's data, through a marriage of particle physics and artificial intelligence.

Anomaly Detection: Unleashing AI on Particle Physics Data:

In most of the traditional searches at the Large Hadron Collider experiments, we use complicated computer simulations to predict how the particles may behave. Based on such simulations, we design our strategy for searching for new particles and new interactions. But we can't always be sure that our simulation models are 100% correct in their predictions while we explore new sets of data. Along with a few scientists from Argonne National Laboratory, our Wisconsin ATLAS research group, and Oklahoma State University, we led efforts in designing a new approach to searching for new physics without relying on those simulations. Instead, we used an Artificial Intelligence (AI)/machine learning(ML) based Anomaly detection technique to find potential anomalous events, which could be interesting for new physics searches.

By anomaly, I mean the unusual or atypical patterns that are distinct from the vast majority of data. For example, imagine someone is looking at a stack of old maps to find some treasures and then suddenly finds a unique map with strange markings, completely different from all the other normal ones. It is possible that those strange markings and directions in that map may lead to an unchartered territory. In the language of data science, finding such strange or atypical or anomalous patterns is called anomaly detection. So, if new physics hides as anomalies in data, one can design a sophisticated anomaly detection technique to probe the data more carefully to find them. Thanks to recent massive developments in the fields of Artificial Intelligence(AI)/machine learning(ML), many innovative anomaly detection techniques have emerged in the industry. We planned to use some of those algorithms for our particle physics research purposes and designed a sophisticated event-based anomaly detection technique to probe our ATLAS experimental data using unsupervised machine learning.

To deal with the complex nature of our experimental physics data, we processed our entire data in such a way that every physics event was represented by a giant matrix of 1287 variables. And then we trained a complicated machine learning algorithm on a very small dataset (we randomly selected 1% of the data) so that the algorithm learns the typical patterns from the vast majority of known physics events.



(a) (b)

Fig 3:(a) Distribution of Anomaly scores of events from our recent study. Based on these scores, our events of interest were selected for further study [Ref. : PhysRevLett.132.081801]; (b) Demonstration of technique to find new physics

In later stages, when the algorithm is exposed to a full set of experimental data, for every event, it calculates scores on the possibility of deviation of that event from known physics. While looking at such scores and distributions for the entire dataset (shown in Fig 3a), we can separate events that display high anomaly scores. Just as one would meticulously scrutinize an anomalous map for clues to uncover hidden treasures, we can carefully analyze the selected anomalous-looking events to identify any unusual behaviors that may lead us to the discovery of new physics, potentially signaling a significant scientific breakthrough.

Our recent results from Event-based Anomaly detection:

In our approach, we used an auto-encoder algorithm (a popular machine learning algorithm) on the data, which was collected by the ATLAS experiment during 2015-2018. Using our algorithm, we separated events with seemingly unusual patterns from our data and probed possibilities of a total of 9 resonances, or channels. In the same way, a di-jet resonance is generated by 2 different jets, these 9 resonances were generated by different combinations of a jet, a b-jet (jet containing b-quarks), a lepton, and a photon. We selected all our physics events when they contained at least one electron or a muon. A Muon is another subatomic fundamental particle, similar to an electron, but 207 times heavier.

We carefully studied different situations and performed detailed statistical analysis while analyzing data from these nine different channels. We wanted to see if our events in a specific unusual region differed significantly from what we'd expect based on our current understanding of physics. Although we didn't find anything significantly different, our study helped us set new limits on how certain unusual events might occur. These limits were better than what we had before, thanks to our new techniques. After comparing our new method to older ones and assessing its likelihood of discovering new physics related to various predicted phenomena by theoretical models, including those related to dark matter, we found that our method increased our discovery sensitivity by more than 300% in some cases. This means that if such theoretical predictions are correct, we will have a much higher likelihood of discovering them using our technique. This is indeed exciting news!

Our study has been the first study by the ATLAS Experiment at CERN to use anomaly detection techniques with unsupervised machine learning acting on full event-level characteristics of LHC events to search for new physics. Due to its novel approach, our results have been published in the prestigious Physical Review Letters (PhysRevLett.132.081801) journal recently.

The Journey Continues:

As our recent study using the Anomaly detection technique has generated optimism and improved discovery sensitivities, I am planning to continue this exploration as a part of the Wisconsin research group. I plan to continue investigating such approaches to widen the scope of new physics searches using Anomaly detection and to bring further improvements to such techniques. As there is a huge amount of experimental data waiting to be analyzed at our ATLAS experiment at the LHC, I will be scanning through billions of particle collisions to find out if new physics are hiding as elusive anomalies, while potentially holding keys to the deepest secrets of our universe.

Who knows what new physics and groundbreaking revelations are concealed within the anomalies, waiting to be unveiled? So, stay tuned as I continue embarking on this captivating journey of exploration in the pursuit of new physics.