# Doctoral School Research Awards Report 2022

## IAIFI Summer School and Workshop

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## 1 Introduction

The Institute for Artificial Intelligence and Fundamental Interactions (IAIFI) is the inaugural AI research institute funded by the National Science Foundation (NSF). The IAIFI is a collaboration of physics and AI researchers at MIT, Harvard, Northeastern and Tufts University, aiming to advance physics knowledge through the galvanisation of AI research innovation and development of novel AI techniques, for the primary goal of advancing physics knowledge - from the most fundamental building blocks to the largest structures in the universe.

In its first ever edition, the IAIFI summer school and workshop took place at Tuft's university from August 1st to August 9th. It aimed to utilise the expertise of IAIFI researchers and affiliates in order to help educate the next generation of researchers working at the intersection of fundamental physics and AI, through both lectures on foundational concepts and hands-on tutorials, in which the theoretical concepts are put into practise. The workshop focused on exposing participants to the cutting-edge techniques currently being forged in both fundamental physics and AI research.


FIGURE 1: The school took place at Tuft's University, Boston.

My research is in the field of experimental particle physics, in which I analyse data taken by the ATLAS experiment, a general purpose detector at the Large Hadron Collider (LHC), CERN. Specifically, I am interested in studying the physics related to the Higgs boson, a fundamental particle in the Standard Model (SM) of particle physics, responsible for giving masses to the other fundamental particles of the SM. At a Hadron collider, such as the LHC, there are many ways to produce a Higgs boson. My research focuses on one of the rarest production mechanisms, in which a Higgs boson is produced in association with a pair of top-quarks, Figure.2, allowing for a direct measurement of the coupling strength between the Higgs boson and top quark, a vital parameter of the SM. However, this process is extremely difficult to accurately measure due to the large irreducible background present at the LHC. This invokes the necessity of Machine-Learning (ML) techniques in order to help discriminate the signal process, i.e events containing a Higgs boson, from all background processes, i.e processes that look similar in the detector. The application of novel ML techniques and state-of-art ML architectures is imperative in constraining measurements of this rare process. The IAIFI Summer School therefore presented itself as a perfect training opportunity for myself to advance my knowledge of cutting-edge ML techniques, that I could apply to my research.

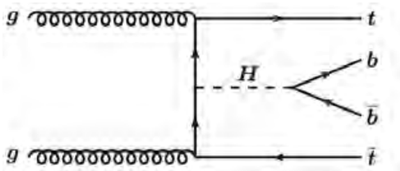


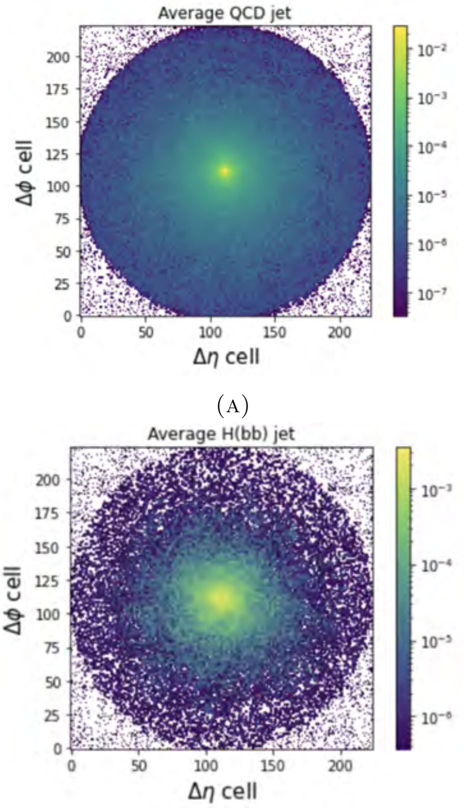

FIGURE 2: Feynman diagram representation of a Higgs boson produced in association with a pair of top-quarks and decaying to a pair of b-quarks.

## 2 The Summer School

The summer school consisted of 5 days of lectures, tutorials and a mini-hackathon. Starting from the foundations of geometric deep learning, where deep learning is an umbrella term for the process of learning complicated relationships by building them from simpler realtionships in a multilayer manner, and geometric in this context refers to generalising deep learning approaches to non-euclidean domains, e.g. graphs and manifolds, we explored topics such as graph neural networks, convolutional neural networks and equivariant neural networks. After familiarisation with the mathematical structure of these algorithms, an exposure to their applications in High energy physics (HEP) was presented. This was in the form of using a convolutional neural network (CNN) to classify the origin of a hadronic jet. Some background knowledge is useful here, so to put it in simple terms quarks and gluons are never seen in isolation in the detector, which is a product of Quantum-Chromodynamics (QCD), the theory of the strong nuclear interaction. Instead, what is observed is a collimated stream of hadrons ( bound states of quarks and gluons), which are commonly referred to as jets. Let's take as example what my research looks at, i.e a Higgs boson decaying to a b-quark pair. The b-quarks will hadronise and form two jets, specifically b-jets. However, there are many ways in a Hadron collider to produce b-jet pairs, like a gluon splitting into a b-jet pair; so how do we know the origin of a b-jet pair we see? This is where state of the art AI algorithms can come to the rescue. There are two steps to what we practised in the tutorial for this topic, the first being how to represent the data you feed into your algorithm, and what algorithm to use. The data is formed of proton collision events containing a plethora of information, such as particle momentum, energy, angles with respect to different planes in the detector and many more. We can represent this data as a 2D jet-image based on the spatial energy spread of the jets, where each pixel in the image has an associated intensity related to the sum of the transverse momentum of the particle, based on its angular position. Since we have transformed our data into a 2D image, it is best to use a 2D CNN classifier. Here, I was exposed to an ML framework I had previously not used, known as Keras, which comes with many ML models pre-built but fully modifiable. Based on these jet images, the classifier was able to accurately classify the origin of b-jet pairs. This gave me an exposure to both data representation techniques for ML and frameworks currently being used at the forefront of research. Other frameworks and libraries used at the school included PyTorch, Jax, and Neural Tangents.

Other subjects covered throughout the school consisted of how to compress the size of neural networks whilst maintaining performance through the use of pruning techniques, the connection between deep neural networks in the large width regime and Gaussian Processes, and using ML to search for new structures and symmetries in data, in the context of Beyond the Standard Model (BSM) physics. Each topic covered came with a dedicated tutorial, which gave me the opportunity to play around with concepts I had learnt in the lectures and see first-hand how to write code for the numerous ML architectures discussed. On top of this, attending the school gave me the fantastic opportunity to network with other young researchers in the field, leading to many interesting discussions and exposure to a vast amount of research currently being conducted. A huge part of being an effective researcher is through the immersion of one's own self in the latest research in the field, which through the generosity of the Doctoral School I was able to achieve.

The summer school culminated in a 4 hour mini-hackathon on the final day, where a choice of three problems was given in which myself and other participants, in small groups, could apply what had been learnt throughout the week, in order to offer a solution to the problem. The problem chosen was based on classifying particle identity in a liquid argon time projection chamber (LArTPC) using a CNN. This was an extremely valuable experience, with it being the first hackathon I had taken part in, allowing myself to both solidify the concepts learnt throughout the school and build on my teamworking skills.




(A)

(B)

FIGURE 3: Hadronic jets represented in an image format

FIGURE 4: The talk given by Yi-Zhuang You, Assistant Professor at University of California, on *Machine Learning Renormalization Group and Its Applications*

## 3 The Workshop

After a weekend spent exploring Boston and synthesising knowledge gained at the summer school, the IAIFI summer workshop commenced with two-days of plenary talks, poster sessions and networking opportunities. I had the opportunity to attend talks given by research engineers at DeepMind and Microsoft Research, plus many plenaries given by academic researchers from the CMS experiment (CERN), Harvard and MIT. This again lead to an extremely large exposure to the breadth of research currently being conducted in AI, with an emphasis on applications to fundamental physics. The ability to meet distinguished researchers who work in industry was also useful, since it gave more visibility to the viability of a research career in industry, as opposed to academia. It was reassuring to see other options are available to those who want to continue doing research, but outside of academia, since this is something of which I am still undecided at this point in my PhD.

FIGURE 5: One of two poster sessions taking place at the IAIFI Workshop, with Anna Golubeva, an IAIFI Fellow, shown presenting her poster on *Understanding and Improving Sparse Neural Network Training.*

## 4 Applications to Research

The IAIFI summer school and workshop provided myself with training in many aspects of ML for fundamental physics applications, from data representation methods to network optimisation. With this, I intend to incorporate my new understanding of Lorentz equivariant networks, a type of deep neural network that incorporates in its architecture an equivariance to the fundamental Lorentz space-time symmetry, into my research. I am also working on a study to use a new variable, specifically the Higgs boson decay angle, into the current ML approach taken by the analysis effort I am apart of, for which I am now in a better position to understand and evaluate the performance of the current neural network being used. I plan to let this be the inception of a career centred on machine-learning, with the school and workshop providing concrete foundations for understanding the tools required to perform this type of research and knowledge of the cutting-edge techniques being employed.

## 5 Acknowledgements

I would like to take this opportunity to thank the Royal Holloway Doctoral School for funding my participation in the IAIFI Summer School and Workshop. It was truly a fantastic experience from which I have gained so many skills applicable to my research. I am beyond grateful. I would also like to thank all of the organising committee at IAIFI, all the lecturers, plenary speakers and tutorial leaders.

FIGURE 6: Downtown Boston, picture taken outside Southside Station on the red transit line.