Institution: University of Oxford		
Unit of Assessment: 09 - Physics		
Title of case study: Higgs Hunters		
Period when the underpinning research was undertaken: 01/01/2000 – 31/12/2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof. Alan Barr	Professor of Particle Physics	01/04/2007 – present
Prof. Amanda Cooper-Sarkar	Professor of Particle Physics	01/10/2005 – 30/09/2019
Dr James Frost	Royal Society URF	14/07/2014 – present
Dr Elizabeth Gallas	Database Software Engineer	19/09/2006 – present
Prof. Claire Gwenlan	Professor of Physics	01/06/2008 – present
Prof. B. Todd Huffman	Associate Professor of Physics	02/06/1997 – present
Prof. Cigdem Issever	Physics Senior Lecturer	14/10/2004 – 31/05/2019
Dr William Kalderon	PDRA	01/04/2016 – 31/07/2016
Prof. Richard Nickerson	Associate Professor of Physics	01/09/1989 – present
Prof. Jeff Tseng	Associate Professor of Physics	01/06/2003 – present
Dr Georg Viehhauser	University Research Lecturer	01/11/2001 – present
Prof. Tony Weidberg	Professor of Physics	01/10/1991 – present
Period when the claimed impact occurred: November 2014 – July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Oxford Physics' key role in the ATLAS collaboration and its search for the Higgs boson led to the development of the citizen science project Higgs Hunters. This two-stage project involved searches for new particles by citizen scientists, and subsequent analysis by UK school students. The citizen science project reached 42,280 participants from over 170 countries. As a result of participation, over 80% of survey respondents reported improved physics knowledge, and 47% were more likely to go on to study physics. In the project's second stage, UK school student researchers from differing backgrounds created and performed their own research projects, and presented them in conferences in Oxford and at CERN. They reported developing a wide range of improved skills, knowledge and engagement.

2. Underpinning research (indicative maximum 500 words)

The Large Hadron Collider at CERN is the most powerful particle accelerator in the world. It reproduces the conditions that existed in the first moments after the Big Bang. Particle collisions are observed in the LHC using large and complex detectors, one of the biggest of which is ATLAS. **[1]** Oxford Physics is one of the leading institutes in the large international ATLAS collaboration. Oxford physicists have major roles including in triggering interesting interactions of the protons, known as "events", reconstruction of these events and studies of backgrounds that can fake real events in the detector. ATLAS is positioned at one of the four points around the LHC at which protons interact, and detects charged particles emanating from the interactions with the "central tracking detector" that contains Semiconductor Tracker barrels that were assembled at Oxford. These are surrounded by electromagnetic and hadronic calorimeters, which measure the energy of all impinging particles and which are themselves surrounded by detectors sensitive to muons. Within the central tracking detector, the paths of charged particles are bent by the solenoidal field from a superconducting magnet, while a separate system of magnets provides a toroidal field within the muon detector. The curvature of the charged particles in the magnetic field is inversely proportional to their momentum. The LHC provides 20 million proton-proton bunch crossings per second, far more than can be recorded by ATLAS. To reduce the data volume, trigger algorithms select up to several hundred events per second that contain interesting features such as muons, electrons or high-energy jets of particles **[2].**

The ATLAS collaboration searched for the Higgs boson, which is predicted to be responsible for the mass of the elementary quarks and leptons. This scalar (i.e. spin quantum number 0) particle was predicted by the Standard Model fifty years previously but was only observed in 2012. **[3,4]** The Oxford group led the discovery of the Higgs boson in decays to W-boson and tau-lepton pairs, observed its decays to tau-leptons and b-quarks, and also led searches for Higgs boson decays to muons and to possible invisible particles that might form the Dark Matter observed in the Universe. Some physics theories under test at the LHC also predict the existence of so-far unobserved particles not included in the Standard Model of particle physics that describes all current data. In such theories, an additional scalar particle mixes weakly with the Standard Model Higgs boson, leading to additional Higgs decays into new particles dubbed 'baby Higgs bosons'. These have a slow decay rate, typically of order nanoseconds, and hence a relatively long lifetime compared to other "Standard Model" particles of a similar mass. **[5]** They can therefore travel for tens of centimetres from the proton-proton interaction point at which they are produced. Their decay is detected by the Semiconductor Tracker as sprays of tracks that originate far away from the interaction point. Such features can be particularly challenging for computer algorithms to reconstruct and are often better identified by the human eye.

3. References to the research (Articles in peer-reviewed international journals)

[1] "The ATLAS Experiment at the CERN Large Hadron Collider" ATLAS Collaboration (including 45 Oxford Physics authors), *Journal of Instrumentation*, **2008**, *3*, S08003. doi: 10.1088/1748-0221/3/08/S08003

[2] "Performance of the ATLAS Trigger System in 2010" ATLAS Collaboration (including 47 Oxford Physics authors), *Eur. Phys. J. C.* **2012**, *72*, 1849. doi: 10.1140/epjc/s10052-011-1849-1

[3] "Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC" ATLAS Collaboration (including 36 Oxford Physics authors), *Physics Letters B*. **2012**, *716* (1): 1–29. doi: 10.1016/j.physletb.2012.08.020

[4] "Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC" ATLAS Collaboration (including 37 Oxford Physics authors), *Physics Letters B*. **2013**, *726*, 88-119. doi: 10.1016/j.physletb.2013.08.010

[5] "Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector" ATLAS Collaboration (including 31 Oxford Physics authors), *Phys Rev D*. **2015**, *92*(7), 072004. doi: 10.1103/PhysRevD.92.072004

4. Details of the impact

Background of "Higgs Hunters" online and extension to schools project

The ATLAS collaboration's search for the Higgs boson is arguably one of the most high-profile scientific efforts of our time, yet at the outset of the Higgs Hunters project in late 2014 there was no way to involve a curious public directly. CERN's popular LHC@home scheme allowed non-specialist users only passive involvement by donating their spare computer resources, while actual participation in research required highly specialised levels of coding experience via CERN's Open Data portal or the Kaggle platform, which ran three machine learning challenges in 2014/15 attracting modest numbers of participants (700-1900).

The "Higgs Hunters" project was launched in November 2014 by the Oxford ATLAS group (PI: Alan Barr) in collaboration with the citizen science platform Zooniverse (who provided the back-end and user interface on which the project ran). The University of Birmingham's public-engagement specialists were consulted in developing and testing the project. Citizen scientists (CSs) were tasked to look for evidence of the Higgs boson decaying to 'baby Higgs bosons' (as described in **[5]**). The project was targeted at existing users of the Zooniverse, and promoted in the media to reach a wider audience. The new particles were expected to produce off-centre tracks in the Semiconductor Tracker barrel detector which are particularly challenging for image-processing software to identify but which can be easily spotted by the human eye. The discovery of a new particle unknown to science would be transformational to the field, which provided good motivation for CSs and was highlighted in media promotion. CSs were asked to classify a selection of both real and simulated data (produced in collaboration with ATLAS colleagues at NYU) for calibration, from events that were pre-selected as likely to contain a Higgs boson (first by the ATLAS trigger algorithm **[2]**, and then based on previous studies which had revealed appropriate selection criteria **[3,4]**). The data were collected from April – December during the 2012 data-taking period, when the LHC was producing proton-proton collisions at around 8TeV.

"Higgs Hunters" on the Zooniverse platform was followed with a schools phase of the project, run in partnership with IRIS (the Institute of Research in Schools). This allowed Key Stage 4 and 5 students the opportunity to analyse the effectiveness of the citizen scientists' classification and to perform their own searches. Selected students later presented their findings at conferences held at the Oxford Physics department and at CERN.

Impact on "Higgs Hunters" participants online

In the first phase of the project, more than 38,000 participants from over 179 countries classified 1,500,000 interesting features on 39,000 distinct images (each classified by 20 different CSs before retirement) **[A]**. This puts Higgs Hunters in the top 2% of projects by number of participants across the entire Zooniverse (which itself is the world's biggest citizen science platform), where to date it is the only particle physics project. Most participants classified a handful of images, with 1,000 classifying over 100, 100 classifying over 1,000, and one individual classifying over 25,000. All registered "Higgs Hunters" participants (28% of total registered+unregistered participants in Higgs Hunters at the time) were invited by email to complete an online survey in June 2016, with 322 responses **[B]**. The survey showed that respondents were 33% female and 65% male (with 2% "other") and represented ages from 16 to 75+, and occupations including students, teachers, engineers, consultants, developers, researchers and retired persons. The best-represented countries in the survey were the USA (25%) and the UK (16%), with a total of 35 countries represented among all respondents. These reported an increased engagement with science, with over 80% responding that their knowledge of particle physics had been improved as a direct result of participation in Higgs Hunters, while 47% indicated that they were more likely to go on to study physics as a result of participation. Many had discussed the project with family (58%) and friends (65%), 87% reported having gone on to read or watch more about science, 29% to study science more formally and 15-20% had attended lectures, science fairs and/or visited museums as a result of their engagement with the project. 97% of the survey respondents indicated that they would like to take part in a future Zooniverse project on CERN physics. An analysis was also performed on the 20,257 comments received between November 2014 and May 2017 from 1,345 users on the "Higgs Hunters" Talk forum **[A]**. The analysis showed that the citizen scientists had formed a community with their own technical language and experts, where analysis of words used on the discussion board which accompanied the project showed an increase in use of advanced technical language, demonstrating deep engagement with the science.

Impact on high school pupils

The second, schools, phase of the project was run in collaboration with the Institute for Research in Schools (IRIS) and allowed school students the opportunity to work through the citizen scientists' classifications of data. The schools phase of the project launched in September 2016. The project was one of eight that IRIS ran in its first year. The students worked with large data files, containing information about the clicks of hundreds of thousands of Zooniverse users. From this, they conceived and then generated their own investigations, choosing an aspect to investigate, producing results and an analysis of the results. To support the students, a detailed "Higgs Hunters" brochure was produced to accompany the data, which presented the concepts in an appealing and accessible way and included links to the UK curriculum. In total, 105 schools downloaded the data from IRIS and 45 schools accessed the supporting resources **[C].** An explanatory webinar aimed at teachers (who watched from 28 schools) and a video covering the launch event have a combined viewing of over 500 views on YouTube **[D]**. Of all the schools that took part in the project, 70% were in the state sector **[**IRIS email 8 July 2020 **D1]**. Despite the challenging nature of the project, 51 pupils from 19 schools showed sustained engagement throughout the process [IRIS email 10 Sept 2020, **D2]**. 17 pieces of student work were produced, with contributions both from individual student researchers and from student teams; these projects were then submitted to the IRIS Library, where they are accessible to other schools in the IRIS network as inspiration. Examples of analysis methods included use of advanced computer coding, machine-learning and pattern-recognition techniques, demonstrating deep engagement with the project. The Physics teacher at Camden School for Girls (where 6 pupils participated) comments "*The whole process has given the students the confidence to talk about Physics beyond the textbook. And for me, as a teacher, it's meant that I've got back in touch with real research and what's going on. It's been inspirational.*" **[D3]**

The student researchers were invited to submit their results as posters. In summer 2018, the 20 student researchers with the best submissions were invited to present their research at a two-day "Higgs Hunters" Conference, held in the Oxford Physics department. The 4 female and 10 male students who were able to attend were from a range of school types (4 from a comprehensive, 9 from academies and 1 from an independent school), while 6 out of 14 came from schools in 'social mobility coldspots' and 8 out of 14 were from black, Asian and minority ethnic backgrounds **[E].** The students wrote up their work, producing Conference Proceedings **[F]** that, following internal review by the ATLAS collaboration at CERN, were the first of their kind to be accepted as an ATLAS Notes publication. The students, who were interviewed by phone after the conference, stated that the opportunity to conduct original research had: increased their physics subject knowledge; helped inform/confirm future choices of study; increased awareness and enjoyment of research; increased understanding of the difference between school physics and research physics; developed a wide range of practical and presentation skills; and developed their confidence and resilience **[C]**. Nine of the students went on to present their research to ATLAS collaborators in September 2019 in a poster session at CERN; a video made for the event has over 7,000 views **[G].** One of the students commented: "*what I was able to fully appreciate at CERN for the first time, was how people from different races, upbringings, and backgrounds, had come together after two world wars and went to extreme lengths to build the world's largest Physics experiment to try and answer these questions. This extended my feeling from last year's conference at Oxford, that Physics itself is inherently open to all people who take an interest in it*". Of the 9 students who went to CERN, 4 have gone on to use their skills as undergraduates in STEM subjects, with others using the skills they developed in other areas including in the creative arts and in industry **[C]**.

In summary, "Higgs Hunters" has evinced, through rigorous and detailed analysis of data collected from participants, an excellent breadth and depth of public engagement. The breadth is illustrated by 38,000 participants from 179 countries, with some activities recording a fraction of BAME participants rarely achieved in the UK. The depth is illustrated by the analysis of the questionnaire responses and the Talk Forum. In addition, participants and teachers involved in the IRIS activity attest to the significant benefits that the project has made to their skills, confidence and appreciation of the scientific method.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] Higgs Hunters survey data (Zooniverse users' survey) giving details of the number of participants, breakdown by categories such as age, gender and occupation, and responses to survey questions.

[B] Journal article: "Citizen scientist community engagement with the Higgs Hunters project at the Large Hadron Collider" A. J. Barr, A. Haas, C. W. Kalderon, *Research For All*, **2018**, *2*, 359–373. doi: 10.18546/RFA.02.2.13. Corroborates numbers of Higgs Hunters participants, numbers of images classified and high levels of engagement with the project's Talk forum.

[C] IRIS Higgs Hunters End of Project Review, confirming schools' participation, data relating to schools, and benefits for the students who took part in the Higgs Hunters conference.

[D] Higgs Hunters YouTube webinar https://youtu.be/jldYYmZp_Gc and launch event https://youtu.be/pNpLB_ViZwE, posted by the Institute for Research in Schools, confirming number of views.

[D1] Email from IRIS (8 July 2020) confirming the fraction of State schools in the project

[D2] Email from IRIS (10 September 2020) confirming the number of schools and pupils who took part in the project.

[D3] IRIS Impact Report (2017-18), reporting feedback from the Physics teacher at Camden School for Girls.

[E] Data on Higgs Hunters conference attendees [Redacted to avoid identification of students]

[F] "Proceedings of the First Higgs Hunters Schools' Conference" ATLAS Collaboration, ATL-OREACH-PROC-2019-002. http://cds.cern.ch/record/2676777?ln=en

[G] STFC YouTube video on visit of students to CERN, corroborating number of views https://www.youtube.com/watch?v=xPidUw_16hw&feature=youtu.be