Institution: University College London

Unit of Assessment: 9 – Physics

Title of case study: Improving public knowledge and understanding of particle physics with the discovery of the Higgs boson and other results from the ATLAS experiment at the CERN Large Hadron Collider

Period when the underpinning research was undertaken: 2008 - 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:
Jonathan Butterworth	Professor of Physics	1995 - present

Period when the claimed impact occurred: August 2013 – December 2020

Is this case study continued from a case study submitted in 2014? Y

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

The on-going energy frontier programme of the Large Hadron Collider (LHC), and the discovery of the Higgs boson in particular, have stimulated interest in physics on a scale unprecedented by any other single experiment. Since 2013, UCL physics researchers who participated in the discovery of the Higgs boson and the ATLAS experiment have contributed to media features, written articles, blog posts, public and school talks, panel discussions and published books on the topic. These efforts have reached millions of audiences worldwide (including in the UK, US, China, France and Italy) and have continued to spark interest in physics and improve public understanding of the nature and purpose of scientific research.

2. Underpinning research (indicative maximum 500 words)

The ATLAS detector, one of two general-purpose particle detectors at the CERN LHC, aims to understand electroweak symmetry breaking and the origin of mass; in the Standard Model the Higgs boson is responsible for these phenomena. The LHC began physics operation in late 2009, and on 4 July 2012 the ATLAS collaboration announced the discovery of a new particle, since shown to be a Higgs boson and consistent with the Standard Model (**R1**). As a result, the Nobel Prize in Physics was awarded to the theorists, Englert and Higgs, in 2013.

The High Energy Physics (HEP) group, part of UCL's Department of Physics & Astronomy, played a major role in the discovery of the Higgs boson. HEP researchers were involved in constructing ATLAS's detector (**R2**). They built electronics for the data acquisition and trigger systems; wrote simulation, trigger and visualisation code for the experiment; and worked on the mechanical engineering of the Semiconductor Tracker (an essential component of the detector), including cable layout and thermal properties. Other major UCL research outputs contributing directly to the impact included the measurement of several key processes for the first time at the unprecedented LHC energies, including "minimum bias" collisions, high energy jet production and the production of electroweak bosons, (for example (**R3**). As conveners of the ATLAS Standard Model group, several ATLAS subgroups, and lead authors on papers, developed a new way of finding Higgs bosons using the boost and jet substructure, overcoming the challenges of high backgrounds and high particle densities in this key channel (**R4**). This has since been essential to the observation of high momentum Higgs production (**R5**) and played a role in the first observation of the Higgs in the decay channel to bottom quarks (**R6**), all of which were UCL-led publications. UCL also made major contributions to work on jet calibration and event simulation (leading the subgroups responsible), and aspects of the discovery analysis, including simulation.

Key UCL researchers responsible for this research were Jonathan Butterworth (Professor,

ATLAS UK PI 2007-2009, ATLAS Standard Model Convener 2010-2012), Emily Nurse (Lecturer and RS URF, convener of soft QCD subgroup 2010), Mario Campanelli (Lecturer, jet subgroup convener 2011), Nikos Konstantinidis (Professor, ATLAS UK PI 2016-2019), Tim Scanlon (Lecturer and Royal Society URF, leader of Higgs to bb analysis group).

3. References to the research (indicative maximum of six references)

R1. Collaboration TA. (2012) Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC 2012. *Physics Letters B* 716(1):1-29. doi:10.1016/j.physletb.2012.08.020
R2. Collaboration TA, Aad G, Abat E, Abdallah J, Abdelalim AA, Abdesselam A, et al. (2008) The ATLAS Experiment at the CERN Large Hadron Collider. *Journal of Instrumentation* 3:S08003–S08003. doi:10.1088/1748-0221/3/08/S08003
R3. Collaboration A, Aad G, Abbott B, Abdallah J, Abdelalim A, Abdesselam A, et al. (2012) Measurement of the top quark pair production cross section in pp collisions at √s=7 TeV in dilepton final states with ATLAS 2012. *Physics Letters B* 707:459-477. doi:10.1016/j.physletb.2011.12.055
R4. Butterworth JM, Davison AR, Rubin M, Salam GP. (2008) Jet Substructure as a New Higgs-Search Channel at the Large Hadron Collider. *Physical Review Letters* 100. doi:10.1103/PhysRevLett.100.242001
R5. Aad G, Abbott B, Abdallah J, Abdel Khalek S, Abdelalim AA, Abdinov O, et al. (2012) Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to a b-quark pair with the ATLAS detector. *Physics Letters B* 718:369–90. doi:10.1016/j.physletb.2012.10.061
R6. Collaboration A (2018) Observation of H to bb decays and VH production with the ATLAS detector, *Phys. Lett. B* 786: 59. doi:10.1016/j.physletb.2018.09.013

References R1, R2 and R4 best indicate the quality of the underpinning research.

4. Details of the impact (indicative maximum 750 words)

There is a clear appetite from the public for accessible information about cutting-edge physics, which helps inform and raise the quality of public discourse around science and research in general; this is perhaps more obviously crucial now than ever before given the challenges we face. UCL contributions to the physics programme of the CERN Large Hadron Collider and related public engagement activities have both met and further stimulated this appetite. This research addresses fundamental questions about the nature of the universe via experiments, deploying advanced technology and engineering. It has led to improved understanding of particle physics concepts and, more widely, of the nature of scientific evidence among the public and pupils, which has changed attitudes, influenced public discourse, and encouraged uptake of opportunities in STEM, as evidenced below.

Increased public understanding of particle physics through blog, books and media activity

Professor Butterworth's *Life & Physics* blog began as a record of the research behind the Higgs boson discovery in an effort to present science and discoveries in a more accessible way. The blog was hosted by *The Guardian* website between August 2010 and August 2018. Subsequently, the blog moved onto Wordpress with associated articles on the Cosmic Shambles network, a platform for people who want to find out more about our universe through science, art, history, philosophy, music and literature. From August 2013 to December 2020, *Life & Physics* posts discussing UCL research have been published weekly attracting 3,700,000 unique visitors (with peaks of approximately 20,000 per day) from many countries, including the UK, USA, Germany, France and Australia (**S1**).

Readers acknowledged the value of the research on particle physics discussed on the blog and the technological advancement it led to: "The physics is important from a fundamental understanding of the nature of matter in our universe and the technological advances have

been monumental in the collider and detectors structure", one comment read, "It's knowledge for the sake of knowing things. I think that's worthwhile. In some ways it's what makes us human" (**S2**). Although the benefits of fundamental research on particle physics are not immediate, these blog posts improved readers' understanding of particle physics and its potential: "Learning how to manipulate the Higgs field may also bring about technologies we can't even dream of today," read one comment, while another said, "Explain why we need to prove Higgs boson exists as at all, why not just believe the theory and move on and start to take advantage of whatever it can be used for? If it has some uses, let's start applying the science to develop the uses" (**S2**). Furthermore, UCL's research described in the *Life & Physics* blog provided a resource for physics teachers to engage students with STEM subjects and led to changes in teaching practice. A secondary school teacher commented: "These posts [on the *Life & Physics* blog] were not only the perfect source for being up to date with new discoveries in particle physics, but also an inspiration and a great resource for teaching physics. Indeed, I have used Professor Butterworth's articles during physics classes on many occasions" (**S3**).

Butterworth's other public engagements with broadcast media in response to public interest included television and radio appearances where he discussed his underpinning research. These include Infinite Monkey Cage (BBC4; 04/07/2017), Today Programme (04/01/2017, 16/01/2018, 27/03/2019), BBC Inside Science (03/09/2015, 29/04/2016, 17/05/2018, 21/06/2018, 28/06/2018). Each episode of Infinite Monkey Cage featuring Butterworth gathered approximately 2,000,000 listeners and 400,000 podcast downloads (**S4**).

The large readership of the blog and the positive feedback evidenced a clear public interest in physics. Consequently, Butterworth wrote two books – *Smashing Physics* (published on 7th May 2015) and *A Map of the Invisible* (published on 6th September 2018) – that provided a systematic explanation of his research in particle physics to the public in an accessible way. *Smashing Physics* and *A Map of The Invisible* have been published in the UK, the US, China, Germany, Taiwan, France, Italy and Russia, with over 36,800 copies and 22,000 copies respectively sold (**S5**). The Royal Society acknowledged *Smashing Physics* for making "the most advanced science around seem within our grasp" and shortlisted it for the Winton Prize (**S6**). Reviews of *A Map of the Invisible* evidence improved understanding of particle physics concepts by its readers: "It [*A Map of the Invisible*] has lots of information regarding particle physics put in a way that's easy to understand for anyone who is new to the field", and "I've been teaching myself about the quantum world for two years and the analogies used in this book provided more than a handful of a-ha moments" (**S7**).

Additionally, in response to demands from schools internationally for accessible content on physics research, ATLAS and TED created the animation lecture *What's the smallest thing in the universe,* detailing Higgs research conducted at UCL and ATLAS. Between its publication on 18th November 2018 and 15th November 2020, the video reached a viewership of approximately 678,000 and received 904 comments. The animation increased viewers' understanding of matter and fundamental particles and inspired them to learn more about the subject as evidenced by viewers' comments: "I've always wondered what the particles that are smaller than subatomic particles were. I also really love how you can explain complex concepts in a really simple way that people can understand and that can be easily accessed," one said. Another noted, "I have known about the elementary particles for years but this quick video just gave me more info about the interactions of the particles then I ever knew. Now it's time for more advanced vids" (**S8**).

Inspiring public and school children through talks about particle physics

Approximately 15,000 people attended talks at which Butterworth and his team discussed the Higgs and related research, including Nine Lessons and Carols for Godless/Curious People (2017 and 2018), End of the World Show (2017), New Scientist Live (2018), British Science Festival (2018), and Royal Institution public lecture (2018). Butterworth also took part in *Sceptics in the Pub* events between 2014 and 2019 (9 events; 40-50 participants each), where the audience engaged in discussion of his research on the Higgs boson. The organisers for

New Scientist Live (2018) highlighted the contribution from Butterworth to the event: "We had 40,000 attendees this year... and the Cosmos stage had 10,595 attendees over the course of the event! […] It was incredible to observe the festival come to life and watch visitors engage so fully with all the talks and exhibits. We want to thank you for taking the time to prepare and present a talk that was both engaging and informative" (**S9**).

Members of the UCL High Energy Physics group, including Professor Butterworth and his team, delivered at least 20 ATLAS-related school talks since January 2015, reaching approximately 1,200 Year 9-13 students in total. Students were interested and engaged in lectures that covered particle physics and aspects of researchers' work as evidenced by a teacher's testimonial: "Approximately 50 of them [students] from year 9-13 attended the lecture that covered not only principles of physics and insights about the ATLAS experiments, but also aspects of the day-to-day life of a researcher. Students were very interested and engaged in the lecture as evidenced by a lively question session after the lecture and a positive feedback. This was an excellent preparation for our trip to LHC and an inspiration for our students. Out of the students in year 12 and 13 during that academic year (2015), 4 of them decided to read physics and 9 chose engineering at university" (**S3**). Another teacher confirmed that students found "the lecture of the professor as very informative and that [the lecture] had given them a better understanding of the particle word" (**S10**). Such engagement effort has contributed to an 66% upsurge of applications to UCL undergraduate Physics courses from the schools that Butterworth and his team have given talks to between 2012/2013 and 2019/2020.

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

S1. Data on *Life & Physics* blog website traffic corroborates readership and number of visitors.
S2. Readers' comments on *Life & Physics* blog in response to 'Could the Higgs boson have been discovered by accident?' article (18/09/2016) corroborate statements provided.
S3. Supporting letter from secondary school teacher (21/04/2020) corroborates statement provided and that blog has served as inspiration for teachers.
S4. Supporting statement from Presenter at Radio 4's Inside Science corroborate number of listeners and downloads.
S5. Data on *Smashing Physics* and *A Map of The Invisible* book sales corroborates number of copies sold.
S6. Royal Society website with shortlisted books for 2015 Winton Prize for Science Books and a judge comment on *Smashing Physics* corroborates statement provided.
S7. Readers' reviews on *Smashing Physics* and *A Map of the Invisible* posted on Goodreads website (28.22.2018; 2.11.2018) corroborate statements provided.
S8. TED-Ed lesson '*What's the smallest thing in the universe?*' published on TED-Ed's YouTube channel (15/11/2018) corroborate viewership numbers and viewers' comments.
S9. Supporting statement from organisers of New Scientist Live corroborating statement provided.
S10. Supporting letter from teacher of mathematics and physics at Watford School for Boys (20/04/2020) corroborates statement provided.