Institution:	The University of Oxford
Unit of Assessment:	9
Title of case study:	[3] Stimulating Engagement in Particle Physics Through Music

1. Summary of the impact

This public outreach programme from Oxford links physics, particle accelerators and music through Einstein who was an enthusiastic violinist. The events have attracted a new audience to engage with science; have increased schoolchildren's interest in science and aspirations for science education; and have supported and inspired science teachers. More than 17,000 people have attended performances across seven countries, including over 8,000 at events for schools; audience satisfaction is very high. Extensive international media coverage has included BBC Radio and Radio New Zealand, television programmes in the US and New Zealand, and many newspaper and magazine articles. The programme has an average of 20 events per year and will continue.

2. Underpinning research

Research in particle physics at Oxford spans all the main areas of particle and particle astrophysics including two of the four experiments at the Large Hadron Collider (LHC) – ATLAS and LHCb – and a thriving theoretical physics group. Experiments in particle physics by their very nature require huge collaborative effort by scientists at universities worldwide. Nonetheless Oxford has made a crucial and distinctive contribution and had research leadership roles in many areas including the following:

- The assembly, alignment and survey at Oxford in 2005 of barrels for the Semiconductor Tracker (SCT) [1], one of the three parts of the Inner Detector of the ATLAS experiment [2]. Under the leadership of Richard Nickerson (Lecturer at Oxford since 1989 and Chair of the ATLAS Inner Detector Collaboration Board 2007-10) and Tony Weidberg (Lecturer since 1991), methods to install accurately and test over 3 million electronics channels were devised. The Inner Detector tracks particles produced in collisions and the reliable performance of the SCT is therefore critical to all data-collection, analysis and discovery at ATLAS.
- Development by Alan Barr and Graham Ross of a methodology to determine the masses of particles, particularly supersymmetric partners and dark matter. These may be produced at the LHC but appear 'invisible' because they cannot be directly detected by the experimental apparatus [3]. Barr joined Oxford as a Lecturer in particle physics in 2007. He was Physics (analysis) coordinator of the ATLAS UK collaboration from 2008-2011. Ross was Professor of Theoretical Physics from 1984 until retirement in 2011.
- Creation of a package of computing algorithms to enable the analysis of collision events at the LHC for the production of mini black-holes [4] by Cigdem Issever (Lecturer since 2007 and convenor of the ATLAS Exotics group 2009-2011) and Jeff Tseng (Lecturer since 2003).
- Analysis of data from the LHC including contributions by Chris Hays (Lecturer since 2007 and current ATLAS-UK Physics convenor) to the discovery of the new particle that has since been established as a Higgs boson [5]. The Higgs boson completes the set of particles in the Standard Model of particle physics and had been sought experimentally for over 30 years.
- A detailed understanding of the distribution of quarks and gluons inside the proton, which is crucial to investigation of signals of potential new physics at the LHC. Brian Foster undertook some of the definitive research in this area at the HERA accelerator in Hamburg, see e.g. [6]. Foster has been Professor of Experimental Physics at Oxford since 2003.

3. References to the research *(Oxford authors underlined; * denotes best indicators of quality)*

1. ATLAS Collaboration (A. Abdassalam et al.: 26 Oxford authors including R.B. Nickerson and A.R. Weidberg) (2008). The Integration and Engineering of the ATLAS Semiconductor Tracker Barrel. *J.Instrum.* **3** P10006. DOI:10.1088/1748-0221/3/10/P10006.
This paper describes the design, construction and final integration of the barrel section of the Semiconductor Tracker.

2. *ATLAS Collaboration (G. Aad et al.: 45 Oxford authors including A.J. Barr, C. Issever, R.Nickerson and A.R. Weidberg) (2008). The ATLAS Experiment at the CERN Large Hadron Collider. *J.Instrum.* **3** S08003. DOI:10.1088/1748-0221/3/08/S08003.
[433 citations, WoS] . *Reference paper for the ATLAS detector.*

3. A.J. Barr, G.G. Ross and M. Serna (2008). Precision Determination of Invisible-Particle Masses at the CERN LHC. *Phys.Rev.* **D78** 056006.
DOI:10.1103/PhysRevD.78.056006. [29 citations, WoS]

4. D-C. Dai, G.Starkman, D.Stojkovic, C.Issever, E.Risvi and J.Tseng (2008). BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension. *Phys.Rev.* **D77** 076007. DOI:10.1103/PhysRevD.77.076007. [58 citations, WoS]

5. *ATLAS collaboration (G. Aad et al.: 35 Oxford authors including C. Hays) (2012). Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Physics Letters B* **716**, 1-29.
DOI:10.1016/j.physletb.2012.08.020 [711 citations, WoS at September 2013]
ATLAS collaboration discovery of a new particle at the LHC, for which Chris Hays at Oxford coordinated the theoretical normalizations and uncertainties for one of the three analysis channels (H→WW).

6. *H1 and ZEUS Collaboration (includes B. Foster and 8 other Oxford authors) (2010). Combined Measurement and QCD Analysis of the Inclusive $e^{\pm}p$ Scattering Cross Sections at HERA. DESY-09-158, 61pp, and JHEP **2010**, 109. DOI:10.1007/JHEP01(2010)109
[122 citations, WoS]
HERA paper on proton structure giving a definitive compilation of key results.

4. Details of the impact *(citations e.g. [A] are to corroborative sources in section 5)*

The impact arises through an outreach programme delivered by Professor Brian Foster that portrays the development and achievements of modern particle physics with illustration through music. The format was first developed in 2005 by Foster with the virtuoso violinist Jack Liebeck (Professor at the Royal Academy of Music and Classical Brit Award winner in 2010) and discusses the quest to unify the laws of physics as Einstein tried, inevitably unsuccessfully, to do. Since Einstein loved the violin and played it all his life, Foster and Liebeck use the violin to illustrate the concepts of modern particle physics and introduce an additional dimension to a science lecture. By appealing to music lovers who might otherwise never attend a science event, they also attract a new audience to hear about physics.

The content of the two shows in this programme concentrates on the answers that accelerators and experimental particle physics are providing to the big questions of why the Universe exists, what are the laws that govern it and why it has evolved as it has. The outreach is thus directly underpinned by research by members of the department: instrumentation and accelerator development and experimental work ensure that the most exciting and topical areas of LHC analysis are communicated, while the theoretical work on many aspects of these phenomena develops the wider context and provides continuity from Einstein's work on unification of the forces.

The first show, "Superstrings", illustrates Einstein's development of General Relativity, discusses why he failed to unify the laws of physics and describes how superstring theory could succeed where Einstein failed. The second, "Einstein's Universe", discusses Einstein's contribution to quantum theory and the development of accelerators that led to the LHC. Both shows describe the construction of the LHC and its detectors, concentrating on the ATLAS Semiconductor Tracker built at Oxford and showing the magnitude and complexity of the assembly of ATLAS. They

conclude with the latest LHC results, including work in which Oxford has played a crucial role [5]. They are interspersed with music that Einstein loved, played by Liebeck; finally Foster and Liebeck play a Mozart duet. The violin is used to illustrate key concepts in the lectures such as the relationship between wavelength and resolution and the vibrational modes of strings; Liebeck not only plays the violin but has an important role in helping Foster explain the science. Some events in larger venues are followed by a concert featuring music that Einstein particularly enjoyed. The conception and delivery of the "Einstein's Universe" event were supported by an STFC Large Award (Science in Society scheme) of £92,521.

Reach

A total audience exceeding 17,000 attended either Einstein's Universe (90 performances) or Superstrings (26 performances) between January 2008 and July 2013 (inclusive). More than 8000 of these attendees were at events given for schools. The events were hosted in the UK, Spain, Germany (including twice in German), France, New Zealand (2 tours), the USA and Japan. A tour in New Zealand in July 2013 performed at 10 venues to a total audience of 2,350. Elizabeth Kerr, a former Chief Executive of New Zealand's Arts Council, reviewed 'Einstein's Universe' on Radio NZ Concert (a predominantly classical music channel) as succeeding in getting "*the music people to the science*" [B]. Other comments included, "*Clear interesting lecture graspable by an arts graduate*". Several YouTube videos are available, two of which were financed by Institute of Physics Publishing and are available on their YouTube page with over 15,000 hits between them [C]. Secondary reach via media coverage is described below.

Significance

Engagement with physics by non-scientific audiences: Questionnaires indicate 95% audience satisfaction with the events [D]. In a more detailed survey of a general audience in Oxford in 2012, 75% of respondents agreed they were likely to discuss physics with someone else as a result [D]. On Radio NZ Concert, Kerr picked out topics from the event including superstrings, mini black holes and the Higgs particle and found it "*a very interesting glimpse into the world of the scientists*" [B].

Increased interest in physics by schoolchildren: Letters and emails received from teachers who attended an event [D] have described immediate interest from students: "*[my pupils] came out buzzing and I had to try and answer some quite complex questions in the bus on the way home", "… the students were discussing it all the way back to the school*" and "*The lecture provoked much discussion at our subsequent Physics lessons"* [E]. Teachers indicate that they are keen to host or attend either lecture again, regarding them as highlights of their wider programmes of extra-curricular activity. One teacher, a winner of an IoP Teacher of Physics award in 2012, wrote,

> "*There is no doubt that lectures such as yours (and yours was one of the very best) raise the profile of the subject and can sow the seeds for youngsters to want to go on to further study in that field."* [F].

As part of such programmes, teachers report that they consider the lectures to have played a significant part in increasing the numbers of students taking Physics at A-level and generating a more positive attitude to science with greater engagement in lessons [F,G].

Influence on future study and career choices: Foster has received letters and emails saying that the lecture has inspired the writers to study physics further, and these are echoed by teachers who consider that the events have inspired students to study physics at university, including by going beyond the school curriculum. A Year 10 pupil wrote in 2010, "*After attending your lecture I understood much that I didn't before... You have inspired me to become a Particle Physicist*." A local newspaper article after a performance in New Zealand in 2013 was headlined simply "*Professor inspires pupils*". More specifically, a UK teacher wrote that students

> "…*were further motivated to research science, and particularly Physics, courses more widely and we believe they have become much more aware of the possibilities within and beyond study at degree level. They have also gone on to attend a residential course at a local university which, previously, they may not have been motivated to do."* [E]

Benefits to schoolteachers: A teacher in New Zealand explained on local television that the clips on YouTube had helped him to decide to take the students to a performance and that demand from

the students greatly exceeded the number he could take. His impression of the event was that "*it'll certainly spark enthusiasm and interest*" and that he would like to use some of the ideas in his own physics classes [H]. A UK teacher writes that a local performance was "*an opportunity to re-appraise and re-evaluate how we present Physics in the classroom and outside of the classroom*" [E], and another that the show "*opened a window to widen discussions with students*".

Further reach through media coverage

The wider reach from these performances has been considerable, with estimated audiences of millions [I] through broadcasts and articles in both UK and international media. For example:

- "Einstein's Fiddle", a 15 minute programme for BBC Radio 4 co-written by Foster, was broadcast in 2009 and 2010 and remains available on the Radio 4 website.
- The performances have been covered in many national and international newspapers as well as in the specialist musical press, for example "The Strad" and "Gramophone" [A].
- Extended interviews with Foster on Radio 3's Essential Classics (5 interviews, October 2012), "In Tune" (2/2/2011) (also including Liebeck) and "Private Passions" (4/5/2008).
- UK regional broadcasting including Jack FM, BBC Radio Oxford and BBC Radio Scotland.
- Coverage of the two New Zealand tours in 17 news publications (2013) and on Radio New Zealand (2009, 2013) included an interview in which Foster described present and future experiments, the Higgs discovery and how physics research has evolved since Einstein [J].

Evolution and sustainability

Both shows have developed continuously in the light of experience and as new results emerge from physics research. Funding for the programme, typically £500 per performance to cover expenses and Liebeck's fees, has come from the STFC, the Nuclear Institute, La Caixa for a tour in Spain, Royal Society New Zealand, ticket sales at events other than at schools and individual hosts. The lectures are planned to continue for the foreseeable future in response to continued strong interest from potential hosts. A recent spin-off, "Particle Partitas", tracing the history of particle physics, was commissioned from the composer Edward Cowie and premiered in June 2012.

5. Sources to corroborate the impact

Reach

A. www.einsteinsuniverse.com contains details of all venues and much of the media coverage.
B. Crossover with music audiences: Review by Elizabeth Kerr, '*Upbeat'*, Radio NZ Concert, 24/7/2013, http://www.radionz.co.nz/concert/programmes/upbeat/20130724.
C. '*When worlds collide: physics meets music'*, and '*Einstein's Universe: the science, the man, the music'*, Physics World YouTube channel, http://www.youtube.com/watch?v=oer7JgH-DEo and http://www.youtube.com/watch?v=TdOAcrwWhpQ and download statistics displayed.

Significance to audiences and teachers

D. Original questionnaire responses and originals of letters and emails, held in Oxford.
E. Director of Sixth Form, Haybridge High School: letter held on file.
F. Head of Physics at St Peter's School, York: email held on file
G. Assistant Headteacher, Lancaster Girls' Grammar School: email held on file.
H. Interview with Warwick Grady, science teacher at Palmerston North Intermediate Normal School on Tararua Television's *'Undercurrent'* programme, 23rd July 2013 and repeats, http://www.youtube.com/watch?v=CptHwVyty6U

Further reach through media coverage

I. UK radio listening figures by Rajar, http://www.rajar.co.uk/listening/quarterly_listening.php
J. 'Playing Favourites' extended interview, Radio New Zealand, 20/7/2013, http://www.radionz.co.nz/national/programmes/saturday/20130720