Research Resumé — Prof. Terry Wyatt FRS

The Standard Model (SM) of particle physics describes the interactions of the gauge bosons (γ, Z, $\mathrm{W}^{\pm}$, gluons) with one another and with the fundamental fermions (the quarks and leptons). Over the past thirty years I have made a number of influential measurements at electron-positron and hadron-hadron colliders that have helped establish the SM as the precise theory of the elementary particles. My work has enabled significant improvements in the experimental precision with which: (a) the SM has been tested and (b) models of the possible new physics beyond the SM (BSM) have been constrained. In order to make these measurements I have developed a number of innovative techniques that have continued to find wide application within the field. In recognition of my contributions to hadron collider physics I was awarded the 2011 Chadwick medal and prize by the Institute of Physics. I was elected as a Fellow of the Royal Society (FRS) in 2013.

My D.Phil. research was performed with the TASSO experiment at what was then the world's highest energy $\mathrm{e}^+\mathrm{e}^-$ collider, PETRA at DESY. This was before the discovery of the W and Z bosons and I chose to work on testing a very important prediction of the SM, namely that fermion-antifermion pairs should be produced with a forward-backward charge asymmetry in $\mathrm{e}^+\mathrm{e}^-$ annihilation (arising from Z/γ interference). I made the first observation of this asymmetry in the $b\bar{b}$ final state. In order to make this measurement I developed the first successful algorithm to use kinematic information to distinguish b quark jets from the jets produced by other, lighter, quarks. I also developed the first successful algorithm to incorporate such kinematic information into a "jet-charge" for distinguishing b from $\bar{b}$ jets. Such algorithms now form part of the standard armoury of high energy particle physics, but at the time were completely new. The value I measured for the forward-backward charge asymmetry in $e^+e^- \to b\bar{b}$ was consistent with the SM expectation that the b quark forms one half of an electroweak doublet of quarks. This was one of the first pieces of indirect evidence for the existence of the top quark.

In order to search for direct evidence for the top quark I was awarded a CERN fellowship and joined the UA1 experiment at the SPS proton-antiproton ($p\bar{p}$) collider at CERN, which was at that time the world's highest energy collider. In fact, just before I joined the experiment, UA1 published a claim to have discovered anomalous events containing isolated charged leptons, missing energy and hadronic jets,. These events were claimed to be consistent with single top quarks, with a mass of around 44 GeV, produced in association with b quarks in the decay of W bosons. I was asked to lead the group in UA1 that was charged with analysing a much enlarged data set in order to confirm the "top quark discovery". This was an unusually large responsibility for a relatively inexperienced postdoctoral fellow to be given in such an important experiment. However, I and my group did not "re-discover" top in the new data set. Indeed, when I independently re-analysed the previously published data set I did not confirm the original "discovery". I found basic technical problems with the original analysis that stemmed mainly from the poor segmentation of the UA1 "gondola" calorimeter. These made it possible for electrons and muons from the semi-leptonic decay of b quarks (that were actually accompanied by soft hadronic activity) to appear to be well-isolated. Such events formed an unaccounted-for background to the claimed signal. For example, if in data events I substituted a clearly non-isolated muon by a Monte Carlo-simulated electron, I showed that the electron could sometimes appear to be well-isolated. This technique was rather novel for the time, but such "event mixing" methods are now well established in particle physics. In order to reduce substantially the probability of a false positive signal, I designed improved algorithms for the calorimeter reconstruction and for defining lepton isolation. My results met initially with very strong resistance from the original analysers and UA1 leadership. It was only after a very difficult period that it became possible to persuade the collaboration to publish an interpretation of the lepton plus jet events in terms of the production of b quarks [20] and a negative search for top quark production [19].

I spent the three years prior to the start of the e^+e^- collider LEP at CERN increasing my experience of detector physics [18] and preparing for the OPAL experiment. During the decade of LEP running, I made a number of important measurements that helped test the SM with a precision several orders of magnitude higher than had been achieved previously. During the first half of this decade LEP ran at a centre of mass energy around the mass of the Z boson. I was the principal author of the first OPAL measurements of the cross section and forward-backward charge asymmetry for Z decays to muon pairs [17] and I coordinated such measurements for all three flavours of lepton pairs throughout this period. I was a prime mover of the OPAL experiment's novel combined analysis of the hadronic and leptonic decays of the Z [16]. I was one of a small group of physicists from the

LEP experiments who collaborated with LEP accelerator physicists to determine precisely the energy of the circulating beams, thus measuring the mass of the Z [13]. During this period I was a principal author of around twenty highly significant papers, which culminated in [11].

During the second half of the LEP era, the centre of mass energy was increased to a maximum of 209 GeV. During this period I studied events containing isolated leptons and missing energy. I used these events to measure the cross section and leptonic branching ratios in the process $W^+W^- \to \ell^+\nu\ell^-\overline{\nu}$. Reference [12] is one example of around five papers in this area of which I was a principal author. In addition, I used these events to search for potential BSM physics, such as SUSY (sleptons, charginos) and charged Higgs bosons. References [14,10] are two example papers of around twenty in this area of which I was a principal author. A particular challenge in this analysis was to achieve sensitivity even in cases where the majority of the available energy would be carried away in the rest mass of invisible new particles (such as neutralinos). In such cases the observable particles would have very low energy and the potential BSM events would be very difficult to distinguish from less interesting SM sources of background (arising from mis-measured particles and particles escaping detection close to the beam direction). I made two important innovations that significantly enhanced the reach of such searches: (a) I developed a decomposition of the transverse momentum of the visible system, one component of which ("a_T") was almost insensitive to mis-measurements; and (b) I demonstrated to OPAL the need for a new sub-detector to veto on the presence of minimum ionizing particles in the region close to the beam direction. This sub-detector, the "mip-plug", was subsequently built and I pioneered its use in physics analyses.

For a two-year period I served as "physics coordinator" for the OPAL collaboration. In terms of responsibility and authority, the position of physics coordinator is second in importance only to that of the collaboration spokesperson. I was responsible for the system of strict internal review that operated for all of OPAL's scientific publications and I played a very active personal role in this review process. I had to ensure that all the important physics analysis topics were being adequately studied and that the groups working on these topics were functioning efficiently. This position gave me the opportunity to learn a great deal of new physics and to influence a very wide range of physics analyses and publications.

As running at LEP was approaching its end the majority of those interested in energy frontier physics moved on to preparations for the next large accelerator at CERN: the LHC. However, I judged that there was an excellent opportunity to pursue a programme of measurements at the upgraded 2 TeV Tevatron $p\overline{p}$ collider at Fermilab, which was due to start running much sooner than the LHC. In addition, in view of the dwindling number of european physicists who had direct experience of doing physics at an energy frontier hadron-hadron collider, I judged it to be an important strategic priority to help prepare a new generation of european physicists before the start of the LHC. Over the previous history of particle physics at the high energy frontier, hadron colliders had typically been the machines at which new discoveries were made. In contrast, e^+e^- colliders, with the much cleaner experimental environment they provide, were viewed as the machines needed to follow up on these discoveries with precise measurements. However, with the huge increase in the numbers of W, Z and top quark events expected at the upgraded Tevatron, compared with those previously available, I saw the possibility to usher in a new era of precision measurements in hadron-hadron collisions. In addition, as the world's highest energy accelerator, the Tevatron offered exciting possibilities for new discoveries, in particular for the SM Higgs boson. In collaboration with colleagues from Imperial College London who shared this vision, I obtained approval from the DØ collaboration and funding from PPARC for a UK group on the experiment. We were subsequently joined by a group from Lancaster University. Although this initiative was not welcomed at the time by all members of the UK particle physics hierarchy, it is now very widely recognized has having been extremely productive and successful. Both in terms of analysis techniques and people, the Tevatron experiments have had a huge influence on the success of the experiments at the LHC.

In 2002 I was invited by Fermilab to take up a fully-paid post as a guest scientist in order to lead the high-level trigger group of DØ in the crucial period leading up to the first collisions and during the first year of data taking. By leading this activity at such a formative period, I exerted a strong influence on the shape of the DØ trigger and thus on the breadth and quality of the entire physics programme that persisted throughout the lifetime of the experiment.

In the first few years of Tevatron running I focused on measuring the rate of $Z \to \mu^+\mu^-$ and $W \to \mu\nu$ boson decays. These processes can be used as "standard candles" at a hadron collider to determine the brightness or "luminosity" of the colliding $p\bar{p}$ beams. Our measurement demonstrated for the first time that there had been a serious error in the normalization of the DØ luminosity measurement. This result was subsequently confirmed by a reanalysis of data from the DØ luminosity detectors. The methods I and my students developed for using $Z \to \mu^+\mu^-$ events to measure the efficiencies with which muons are triggered and reconstructed have been used ever since by the collaboration and, together with a correct determination of the luminosity, have had a decisive influence on the quality of all of DØ's scientific results. Such methods are now standard at the LHC.

In 2004 I was elected by the 650-strong DØ Collaboration to lead it as "Spokesperson". As its leader I exerted a decisive influence over the entire scientific activity and output of the collaboration. During the three-year period I led DØ, the collaboration published more than 80 scientific papers in prestigious international journals and presented more than 500 invited talks on DØ results at international conferences. One of the scientific highlights under my leadership was DØ finding the first evidence for B_s^0 meson matter-antimatter oscillations [9] (the most cited paper in experimental particle physics in 2006). Finding these matter-antimatter oscillations at a rate consistent with that expected in the SM placed very severe constraints on models of BSM physics. Another DØ "first" during this period that was particularly close to my heart was finding the first evidence for single production of top quarks [8] (more than twenty years after the UA1 result discussed above). As spokesperson I followed the development of these, and a large number of other, analyses very closely; I suggested improvements to the analysis procedures, additional cross checks, etc.

My current research focuses on the interplay between electroweak and QCD physics and involves close contact between experimental measurements and particle physics phenomenology. At hadron colliders the study of electroweak physics and QCD go hand in hand. The beam particles are composite objects, whose constituents undergo complicated QCD interactions that can make the analysis of the hard parton-parton scattering processes of interest difficult to interpret. Residual uncertainties in such QCD effects (such as the properties of initial state gluon bremsstrahlung, scale uncertainties of fixed order calculations, parton distribution functions, etc) often dominate the systematic uncertainties on measurements of electroweak variables and on the interpretation of searches for physics beyond the Standard Model at hadron colliders.

Two important strands of this recent work have involved applying in a hadron collider environment the ideas behind the a_T variable I introduced at LEP (as discussed above). Firstly, I have developed novel techniques [5,3] for measuring the transverse momentum distribution, p_T^Z, of Z bosons at hadron colliders. The variable "ϕ^*_η" is defined using only the directions of the observed leptons; it is measured with much better experimental resolution than p_T^Z and it yields measurements that are much less susceptible to the sources of experimental systematic uncertainty that have limited the precision of the previous world's best measurements of p_T^Z. Using this technique and data from DØ I have performed measurements of unprecedented precision [2], which exposed deficiencies in what were at that time the state-of-the-art QCD predictions for vector boson production at hadron colliders. These new experimental techniques and measurements have stimulated considerable interest in the theoretical particle physics community; theoretical calculations of the distribution of the new variable ϕ^*_η have been performed and improved predictions using numerical and Monte Carlo methods have also been made. This new experimental technique opens up an exciting programme of measurements to be performed at the LHC. The distribution of ϕ^*_η is already being measured by the ATLAS experiment. In the longer term I shall study using ATLAS data the dependence of ϕ^*_η on: incoming parton flavour (u, d and gluon), momentum fraction, x, and lepton pair mass, and search for possible differences in "valence" and "sea" quark contributions.

As a second application in a hadron collider environment of the ideas behind the a_T variable, I have developed a new technique for improving the selection of events containing missing transverse momentum. This new technique led in large part to the first observation of the production of pairs of Z bosons at a hadron collider [7,6]; this is the smallest cross section process ever observed at a hadron collider and was an important step in demonstrating sensitivity to processes involving the Higgs boson. A follow-up analysis I performed recently [1] has produced the most precise measurements to date of the cross sections at a hadron collider for the two processes of WZ and ZZ vector boson pair production. I also applied this new technique to the selection of candidate events for the process $ZH \to \nu\bar{\nu}b\bar{b}$ [4]; this contributed to the first evidence recently observed by DØ and CDF for the decay of the Higgs boson to a $b\bar{b}$ pair. Such ideas will continue to have influence in the future. For example, ATLAS used a_T as a discriminating variable in its recently published discovery of the Higgs boson.

My scientific judgement and integrity are internationally respected. I have served on all of the most important scientific committees at CERN, including a 3-year stint as chair of the LHC experiments Committee (LHCC), as well as a number of other such bodies in Europe and North America. When the world leaders in particle physics gather to discuss long term strategy, I am one of the people asked to give important plenary talks. Having experienced at first hand some pretty appalling behaviour by a few world-renowned physicists, I take very seriously my personal duty to encourage the development of young scientists by promoting a spirit of open scientific debate, even in potentially difficult or controversial situations. I believe passionately that the brightest and most enthusiastic undergraduates should be given the opportunity to participate in original scientific research; for example, two of the authors of [3] were undergraduates.

In particle physics there tends to be something of a divide between those who design and build detectors and those who analyse the data produced by those detectors. I have always tried to bridge this divide. In my experience the best analyses are performed by those who really understand how the experimental apparatus works. I have been similarly active in promoting close collaboration between the experimental and theoretical particle physics communities. For example, I initiated the programme of jointly supervised theory-experiment PhD students in Manchester; currently I supervise two such students.