WILLIAM JAMES STIRLING CBE

4 February 1953 — 9 November 2018

W James Stirling

WILLIAM JAMES STIRLING CBE

4 February 1953 — 9 November 2018

Elected FRS 1999

By A. D. Martin FRS[1] and B. R. Webber FRS[2]

[1] *Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK*

[2] *Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK*

James Stirling's wide-ranging contributions to the development and application of quantum chromodynamics were central in verifying QCD as the correct theory of strong interactions, and in computing precise predictions for all types of collider processes. He published more than 300 papers on a vast range of phenomenological topics, including some of the most highly cited of all time in particle physics. His research, always full of insight, focused on the confrontation of theoretical predictions with experimental results. Amongst many key contributions, he developed the helicity amplitude method and used it to show that the CERN 'monojet' events, thought to be a possible signal of new physics, were due to vector boson plus jet production. The method has since facilitated the calculation of many other important processes. At Durham he formed a famous long-standing collaboration that set the standard for determining the quark and gluon distributions in the proton. Besides his intellectual brilliance, his personal qualities of humility, modesty, diligence and fairness made him an outstanding scientific leader and administrator. He played a major role in the foundation of the Institute for Particle Physics Phenomenology in Durham and served as its first Director. In 2005 he was appointed Pro-Vice Chancellor for Research at Durham. He moved to the Cavendish Laboratory in Cambridge in 2008, becoming Head of the Department of Physics in 2011. Then in 2013 he was appointed to the newly created position of Provost, the chief academic officer, at Imperial College, London, from which he retired in August 2018.

Early years

James Stirling was born in Belfast in 1953, the son of John and Margaret Stirling, who were primary-school teachers. He was educated at the Belfast Royal Academy in Northern

http://dx.doi.org/10.1098/rsbm.2019.0031

Published by the Royal Society

Belfast, at the height of the Troubles. He was an exceptional pupil, gaining grade A in *five* subjects at A level. He was Head Boy of the Academy and, although very studious, had a wide range of interests. He was a gifted rugby player in the Academy's first 15. He was also a talented musician, able to turn his hand to almost any instrument, especially the piano, trumpet and guitar.

He took the Cambridge University entrance examinations in 1972 and was awarded a Scholarship to read Natural Sciences at Peterhouse. After one week as an undergraduate he decided, against advice, to transfer to Mathematical Sciences. Nevertheless he gained Firsts in Part IB and Part II of the Mathematical Tripos and a Distinction in Part III. He graduated BA in 1975, and continued at Peterhouse to take a PhD (1979) in Theoretical Particle Physics in the Department of Applied Mathematics and Theoretical Physics (DAMTP). He won a Smith's Prize for Mathematics in 1978.

He married Paula, his sweetheart from the Belfast Royal Academy, in 1975 after they had both graduated.

Graduate study in Cambridge

James started his PhD under the supervision of Professor John Polkinghorne (FRS 1974). At that time the structure of the proton, as revealed by electron scattering experiments at the Stanford Linear Accelerator Center, was the focus of interest of the DAMTP high-energy physics group. The experiments had shown that the proton has charged pointlike spin one-half constitutents, consistent with the quarks postulated by Murray Gell-Mann (ForMemRS 1978) and George Zweig. It was initially expected that, if the quarks were genuinely elementary objects with no substructure and no intrinsic scale, the scattering data should exhibit a scale-free behaviour known as Bjorken scaling. Instead, however, there was a mild scaling violation, in the form of a logarithmic dependence on the momentum transfer to the electron. With the advent of quantum chromodynamics (QCD) in the early 1970s, it became clear that scaling violation was due to the quantum field of gluons binding the quarks together. Although strong enough to confine the quarks inside the proton, the gluon field becomes weaker at the shorter distances probed in high momentum-transfer collisions, leading to logarithmic scale dependence and asymptotic freedom of the quarks.

In his thesis, entitled 'Deep inelastic processes in asymptotically free theories', James verified these features of electron–proton scattering by extending an earlier Feynman-diagrammatic treatment due to Polkinghorne (1976), based on spin-zero gluons, to the full complications of QCD, with its spin-one self-interacting gluon field. In (1)* he applied a similar approach to the process of lepton pair production in hadron–hadron collisions. Drell & Yan (1970) had used a simple scaling model to compute the probability for a quark in one hadron to annihilate an antiquark in the other and produce the lepton pair. The cross section for a particular invariant mass of the pair was obtained by convolution of the momentum fraction (x) distributions of the quark and antiquark in their respective hadrons, the so-called parton distribution functions (PDFs).[1] James showed that the same holds true in QCD, provided the scale-dependent PDFs are evaluated at a momentum-transfer scale equal to the invariant mass of the lepton pair.

* Numbers in this format refer to the bibliography at the end of the text.

[1] In QCD the term parton, invented by Feynman, denotes a quark, antiquark or gluon constituent/part of a hadron.

In 1977 Polkinghorne resigned his chair and left physics to train for the Anglican priesthood. James's supervision in his final year was taken over by Peter Landshoff, who has stated that by then 'James was already a world-leading expert on QCD and I learnt far more from him than he from me'.

Postdoc in Seattle

For his first postdoctoral position, James went to the University of Washington in Seattle, where Steve Ellis and his collaborators had been studying hadronic final states in electron–positron annihilation. This was a fertile testing-ground for QCD in view of the plentiful data coming from the new PETRA e^+e^- collider at DESY in Hamburg. A promising observable was the energy-weighted two-particle correlation (EEC for short), which they had computed in fixed-order perturbation theory. This is an acceptable first approximation in angular regions away from the back-to-back (180°) configuration, where the bulk of the data are situated but the coefficients in the perturbative expansion blow up double-logarithmically. The Seattle team had a conjecture for the summation of the enhanced terms to all orders in the QCD coupling constant α_S. With James on board, they were able to prove the conjecture and to include the first subleading term as well as the scale dependence of the coupling (2). A conceptually similar situation occurs in the Drell–Yan process when the transverse momentum of the lepton pair is much smaller than its invariant mass, and they were able to treat that problem as well (2,3). Other groups were working simultaneously on such issues, notably the Leningrad team of Dokshitzer, Diakonov and Troian (1980). East–West communication was difficult in those days but eventually the parallel efforts led to deeper insights.

Research Fellow in Cambridge

After two years in Seattle, James returned to DAMTP in Cambridge as a Junior Research Fellow of his old college, Peterhouse. Amongst many other projects, he was able to extend work on the Drell–Yan process at small transverse momentum, joining Christine Davies, then a graduate student at the Cavendish Laboratory, in a calculation of all the logarithmically enhanced terms up to the second order in α_S (4). This allowed the most precise comparisons to date with experimental data from Fermilab and CERN, including the first results on the newly discovered W and Z bosons (5). Later work by Kulesza & Stirling (39), as well as many others, steadily refined the predictions and included non-logarithmic terms, but the challenge of computing all enhanced terms of the next higher order was only met some 27 years later (Becher & Neubert 2011).

CERN Fellow and staff member

In 1983 James was awarded a CERN Fellowship and left Cambridge for Geneva. This was a very exciting time to work at CERN. Since 1981 the Super Proton Synchrotron had been operating as a proton–antiproton collider, based on the ideas of Carlo Rubbia (ForMemRS 1984) and Simon van der Meer. With beam energies of 270 GeV, this gave collisions at a centre-of-mass energy of 540 GeV, much higher than the 27 GeV corresponding to the original 400 GeV proton beam colliding with a fixed target. Furthermore, a large fraction of the momentum of the antiproton beam was carried by antiquarks, just as that of the proton was carried by quarks, making the collider an ideal machine for producing new particles by quark–antiquark annihilation. By 1983 this had led to the discovery of the W and Z bosons, the mediating particles of the weak interaction, by the UA1 and UA2 Collaborations. When the boson decays into a pair of leptons, this is essentially the Drell–Yan process that James had worked on in Cambridge and Seattle.

Vector bosons plus jets

Using his expertise in QCD, James worked with Steve Geer of UA1 on understanding those W and Z production events that had in addition a jet of hadrons in the final state (6). The idea that a jet is due to an ejected high-momentum parton fragmenting into hadrons with the same total energy and resultant momentum had already proved successful in other contexts. They showed that vector boson plus jet events could be explained in the same way, using the QCD predictions for the emission of a quark or gluon along with the boson.

Another CERN Fellow, arriving at about the same time as James, was Ronald Kleiss from the Netherlands. While a postdoc at Leiden, Kleiss (1984) had developed a novel method for calculations in quantum electrodynamics. The standard method involved calculating the squared modulus of the amplitude for a process, summed over initial and final helicity states, which generated huge numbers of terms and required laborious Dirac algebra for multiparticle processes. Instead, Kleiss computed the complex helicity amplitudes directly using so-called spinor techniques. Together at CERN, Kleiss and Stirling extended this method to QCD and to processes involving massive vector bosons, culminating in their landmark publication (7).

The helicity amplitude method opened the way to calculations that had previously seemed too difficult. With Steve Ellis, now on leave at CERN, they used it to perform the first complete predictions of vector boson plus two jet production in hadron collisions (8). This allowed them to show in (9) that the background from this process would be too great for vector boson pair production to be detectable if either of the bosons decayed hadronically, so that the search for these important processes should concentrate on double leptonic decays. And indeed W boson pair production was finally observed in this way at the Fermilab Tevatron in 1997, confirming the predictions of QCD and the unified theory of electroweak interactions, together known as the standard model (SM).

The Kleiss–Stirling technique and developments from it have since been used by others in a huge number of calculations, and today they form the basis for automatic computer generation of predictions for processes in the SM and a range of its hypothetical extensions.

Monojets

In early 1984 the UA1 Collaboration published a paper reporting their detection of ‘monojet’ events, with a single high-momentum jet and no other visible high-momentum objects in the final state. This meant that there was a lot of unbalanced momentum in directions transverse to those of the incoming beams, which must be carried by energetic invisible objects: ‘missing transverse energy’ or MET for short. An obvious explanation, considered in the UA1 paper, was Z plus jet events in which the Z boson decays to a pair of neutrinos.

However, the predicted rate was too low: there was an excess of five events with MET greater than 40 GeV.

The excess events caused great excitement as a possible signal of a new phenomenon beyond the SM. An explanation favoured by many theorists was supersymmetry, in which each SM particle has a partner with spin differing by a half-unit. For example, the spin one-half quarks would each have a spinless ‘squark’ partner. If the scale of supersymmetry breaking were large enough, a squark would decay into a quark plus an energetic invisible spin one-half ‘neutralino’, the supersymmetric partner of an SM boson. Then squark–antisquark pair production would lead to monojets with high MET when the momenta of the decay quarks were aligned.

With their helicity amplitudes for vector bosons plus jets, Ellis, Kleiss and Stirling were in a good position to study in detail the possible SM origins of the monojet events. In particular, there was the possibility that W boson plus jet production could contribute as well as Z plus jets, if the W boson decayed leptonically. The W decay products would be an invisible neutrino plus a charged (e, μ or τ) lepton, so the issue was how often the charged lepton might also escape detection, either by having too low an energy, or by being hidden inside the jet, or by being directed outside the angular coverage of the detector. A τ lepton could also decay into a neutrino plus some hadrons, which might look like or merge into a jet.

The helicity amplitude method had the further advantage that it gave complete information on the polarization of the vector boson, so that the distribution of its decay products could be reliably predicted. Thus James and his collaborators were able to show convincingly that the monojets could be explained by accumulation of all the small effects outlined above (10,11). There was a kind of showdown at a meeting on proton–antiproton collider physics at Saint-Vincent, Aosta Valley, in February 1985, in which Stirling and Ellis spoke after the UA1 monojet presentation and convincingly refuted the suggestions of a new phenomenon such as supersymmetry.

In a way this was the start of an era extending to the present day, in which the undeniable theoretical attractiveness of low-scale supersymmetry has been relentlessly ground away by the weight of experimental data.

Durham

As emphasized above, already during his graduate studies at Cambridge, in the early days of QCD, James was well practised with using Parton Distribution Functions (PDFs). However, not until 1986 did James consider the determination of the parton distributions of the proton directly from experimental data. The catalyst for doing this was Durham. By then he had a world-wide reputation for innovative research, and had established his special gifts of presenting his results in a clear and accessible manner. At this time faculty positions in particle theory were few and far between, but in 1986 he secured a position, against strong competition, at Durham University and left his prestigious Staff Member appointment at CERN. He joined a small, active, outward-looking group. He stayed in Durham for 22 years.

These years at Durham were particularly successful. He now taught undergraduate classes and supervised postgraduate students. With his inclusive, humble nature he excelled at both tasks. Moreover his innovative research continued unabated. Immediately on arrival he teamed up with Alan Martin and with postdocs at Durham on a variety of projects, whilst also continuing his fruitful research with colleagues at CERN and elsewhere.

Global PDF analyses

One of the first projects with Alan Martin deserves special mention. They were joined by Dick Roberts from the Rutherford Appleton Laboratory in what appeared to be a well-defined small project, but which soon blossomed into setting the standards in the determination of the PDFs of the proton from all available world-wide data; an activity which continues to become increasingly important to this day. The small project was to improve the limits on the number of light neutrinos (N_ν) and the mass of the top quark (m_t) from data on W and Z boson production. A crucial ingredient is knowledge of the ratio of down to up quark densities in the proton at a specific kinematic point. At that time the ratio was determined by a leading-order (LO) analysis of data on lepton scattering on proton and deuterium targets. By looking critically at the data and using next-to-leading order (NLO) expressions (that Dick had used a few years earlier) they were able to significantly reduce the uncertainties involved (14).

The next step followed soon after. They presented the first ever NLO fit to all available deep-inelastic lepton–nucleon scattering data to determine sets of parton distribution functions (the so-called MRS parton sets) (17). This was a truly global NLO analysis in which data on J/ψ, jet, W and Z boson production were also used in attempts to distinguish between PDF sets with different behaviour of the gluon PDF of the proton at low x. The gluon is predominant in the kinematic region where partons carry a small fraction x of the parent proton's momentum. The uncertainty of the gluon PDF in this region continues to attract intensive study to this day.

There soon followed Martin, Roberts and Stirling (MRS, figure 1) papers which set standards for subsequent global parton analyses. First, it became clear that including more different types of data, however sparse, can resolve disagreements between conflicting experimental measurements of the same observable. An early example (19) was the use of Drell–Yan data in an attempt to resolve a troubling discrepancy between μp scattering data from the EMC and BCDMS experiments at CERN, which even at this early stage favoured the latter. Another innovation, which is now standard practice in PDF studies, was to use the PDF sets to give benchmark predictions for other processes which may be observed in collider experiments (20).

New and different types of data were being obtained and MRS were continually improving their analysis. A more definitive set of partons was presented in (22). The updated fit included re-analysed SLAC data on electron scattering, new information on the n/p muon scattering ratio; and incorporated prompt photon production and Drell–Yan data to more tightly constrain the gluon and sea quark PDFs. As a consequence W, Z, jet and heavy quark production at present and future colliders were predicted with greater accuracy.

Another pivotal paper around this time was when MRS teamed up with Jan Kwiecinski (from Krakow) to perform a very early study of PDFs at low x (23). The analysis went beyond the conventional ("leading twist") formalism to include shadowing corrections and, most importantly, gave implications of these corrections for other processes.

Routinely MRS responded to the implications of new measurements and emphasized the importance of examining data from *all* processes which involved PDFs of the proton. Their numerous contributions in the 1992–6 period resulted in regularly updated parton sets. That of (34) is particularly interesting since by then precise measurements from the HERA electron–proton collider in Hamburg were starting to dominate ep scattering data, and the Fermilab jet data were becoming influential in the global PDF analysis. One consequence was that the value of the QCD coupling extracted from the global analysis was changed from $\alpha_s = 0.113$ to a value in the range $0.116-0.120$, compatible with the present world average.

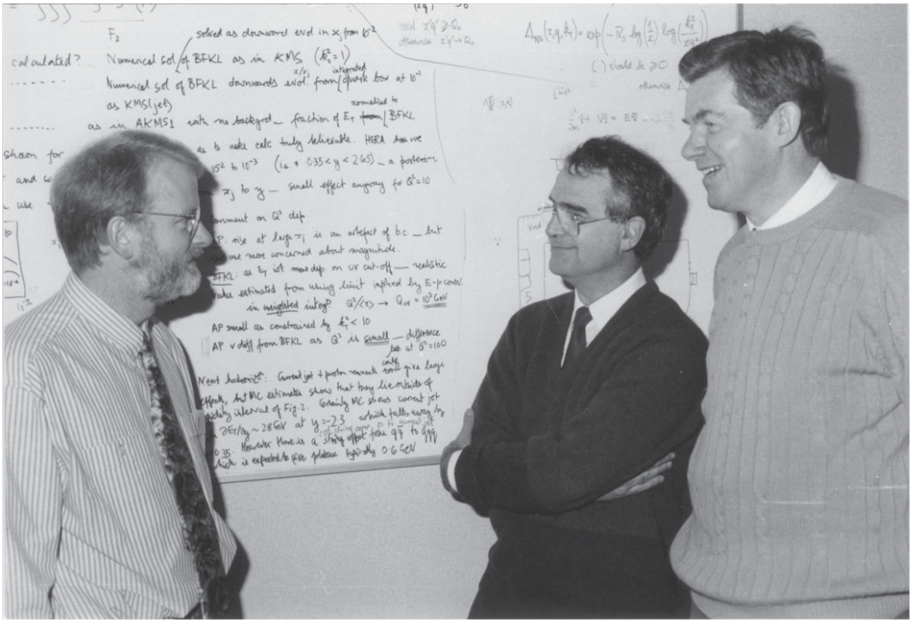

Figure 1. James Stirling, Dick Roberts and Alan Martin (MRS) in 1994.

As ever, James was keen to explore new areas, particularly when there were new promising research students available to work with. In this period two new PDF areas were explored. First, with Peter Sutton, MRS determined the PDFs of the pion for the first time in an NLO ‘global’ analysis of data from Drell–Yan and prompt photon experiments (28). The pion PDFs were found to be compatible with the first two moments of the pion valence quark distribution obtained from first principles by lattice simulations of QCD. Then another student, Thomas Gehrmann, and James performed extensive early work on determination of the polarized PDFs of the nucleon (35).

In 1997 Robert Thorne became an important addition to the MRS collaboration. At that time there was a large influx of new, and more precise, data from the experiments at CERN, HERA and Fermilab on a large range of processes. A major new global PDF analysis was undertaken and yielded a much more constrained set of partons (37). Importantly the analysis contained a much-improved treatment of the heavy quark PDFs. Moreover, the paper described in detail those data that put constraints on the various parton PDFs. For example, the charge asymmetry of $W^{\pm}$ production at Fermilab was sensitive to the *d/u* quark ratio at $x \sim 0.05$. A paper (38) on the scheme dependence and higher-twist (low-scale) implications of this parton set followed soon after.

The next major PDF contribution was (43). The paper opened with the comment “A precise knowledge of PDFs is absolutely vital for reliable predictions for the signal and background cross sections at the forthcoming LHC at CERN”. This study focused on *W* and *Z* production and conservatively estimated the error on the predictions to be $\pm 5\%$. The paper contained the plot shown in figure 2, so characteristic of James. A simple plot, yet so illuminating. He said if he had received £5 every time this plot was copied then he would be a rich man.

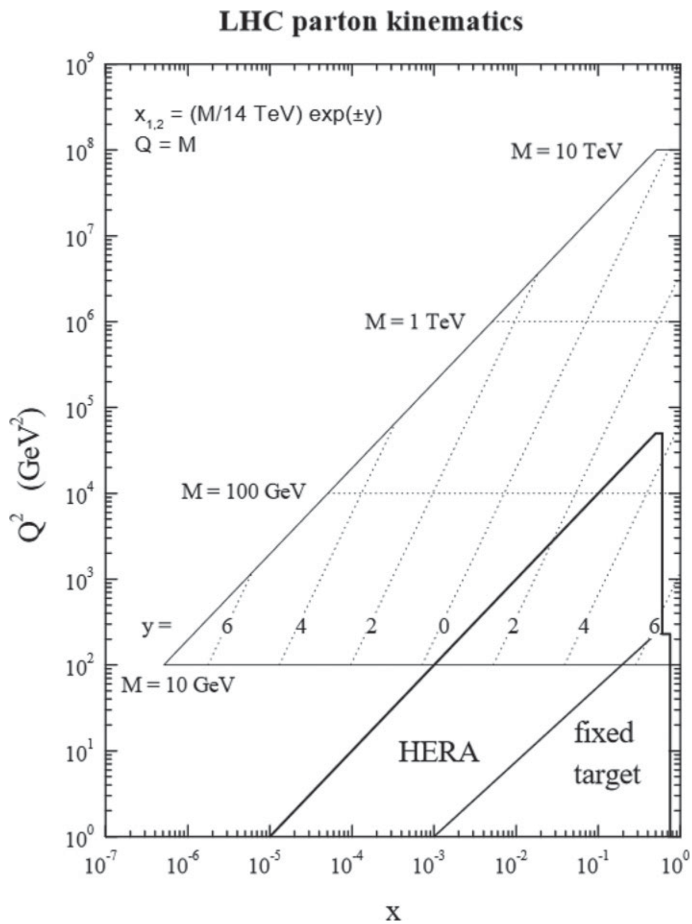

Figure 2. An example of an illuminating plot due to James, from Ref. (43). The large triangle shows the kinematic region accessible for the production of an object of mass M at the LHC of energy 14 TeV.

More data in 2001 allowed MRST (figure 3) to improve the PDFs (particularly of the gluon) and the accuracy of the value of α_s (45). This analysis was the basis of detailed studies of the uncertainties in the predicted PDFs arising from experiment (47) and due to theory (48). In (47) it was shown how to treat the experimental uncertainties in a much more quantitative way, so parton sets could be obtained with meaningful errors. On the theory side (48), one source of uncertainty comes from the change in going from an NLO to an NNLO analysis. An NNLO analysis requires the knowledge of the relevant splitting and coefficient functions at NNLO. The latter were known, but the former were not. However, valuable partial information was known, which MRST found limited the possible uncertainty in the NNLO contribution down to quite small values of x (44). This enabled James and his collaborators to carry out the first ever NNLO global PDF analysis (46).

Another pioneering development was the first inclusion of QED contributions in available PDFs (52). The input photon PDF was modelled on the evolution of emission from valence

Figure 3. Alan Martin, Robert Thorne, James Stirling and Dick Roberts (MRST) on the occasion of the 2017 Stirling Lecture given by Fabiola Gianotti (ForMemRS 2018), Director General of CERN, arranged to coincide with Alan's 80th Birthday. (Online version in colour.)

quarks at low scales. This is similar in principle to the modern version. One consequence was that the isospin asymmetry in valence quarks automatically changed in the right direction to reduce the troubling 'NuTeV' anomaly which existed at that time.

Dick Roberts retired in 2005 and a little later Graeme Watt joined the PDF project. MSTW presented the first 'full' set of NNLO PDFs with heavy quark thresholds properly included, and described the Drell–Yan data in terms of double differential distributions (53). The next paper was 100 pages in length (54). It presented, in detail, definitive sets of partons ready for the inauguration of the LHC. Many novel features were introduced in the analysis, including: a more sophisticated way of determining the uncertainties due to the experimental errors of the many different data sets; an improved way of including heavy quarks; extending the parametrization of the input gluon PDF; including the resummation of high-order effects in W and Z production; studying the variation of PDFs with scale or jet algorithm; allowing $q \neq \bar{q}$ for non-valence quark PDFs. It is said (STFC 2017) that this MSTW paper has the highest number of citations of any paper with only British authors. It is appropriate that the four authors come from England, Ireland, Wales and Scotland respectively.

The next paper (55) was also heavily used. As always James looked in detail at the implications, and there it was shown, for the first time, that uncertainties on α_s and on the PDFs, when both are determined in a global fit, can be accounted for *simultaneously* in calculations of cross sections. In addition, PDF sets with different fixed α_s values were provided to allow further studies by the general user. As illustrations, these PDF sets were used to calculate cross sections for W, Z, Higgs boson and inclusive jet production at the Tevatron and LHC.

By now James had moved to Cambridge, but his enormous influence on the global PDF studies remained. The sensitivity of global PDF analyses to variations of the heavy quark masses was studied (57). This paper also contained PDF sets in fixed flavour number schemes. Ref. (67) describes his final contribution to global PDF studies. In this paper the input PDFs were parametrized using Chebyshev polynomials which much improved the stability of the analyses. In particular the 'nuclear' corrections to the deuteron structure function were brought under control. This paper contains a beautiful section due to James on lepton charge asymmetry in $W^{\pm}$ production and its implications for PDFs. There you will find two of his characteristically illuminating plots.

Jet algorithms

As we have seen, jets of hadrons play an important role in particle physics as the signatures of high-energy parton (quark or gluon) emission. For unambiguous comparisons between experimental data and theoretical predictions, a jet-finding algorithm that can be applied in the same way to the hadronic final state of a collision and the partonic final state of a perturbative QCD calculation is essential. Such an algorithm was formulated by the JADE Collaboration working at the PETRA electron–positron collider (Bethke *et al.* 1988). It was based on the following simple successive recombination procedure: amongst all the final-state objects (hadrons or partons), find the pair with the smallest invariant mass and combine them into a new object with the resultant momentum. Keep on doing this as long as all invariant masses are below some resolution scale value. The resulting objects are jets resolved at that mass scale.

In August 1989 the new LEP electron–positron collider at CERN came online, with sufficient energy to produce huge numbers of Z bosons, many of them decaying into hadronic final states. These copious new data highlighted important defects of the JADE algorithm. Experimentally, it sometimes constructed jets out of hadrons moving in very different directions, far from the jet axis, and theoretically, the predictions for different numbers of jets did not reveal any underlying pattern. In a key 1990 work (21), James and Nick Brown, a young postdoc at Rutherford Laboratory, showed that these defects were related: the JADE algorithm misallocated regions of multi-jet phase space.

A turning point occurred at a December 1990 workshop on jets in Durham. As Siegfried Bethke of the JADE Collaboration presented results using their algorithm, Yuri Dokshitzer (free at last to travel from Leningrad) spoke up from the back of the room: QCD dynamics implies that you should use relative transverse momentum (k_{t}), not invariant mass, as the criterion for combining objects. Overnight, Bethke changed his code and redid the analysis: the results looked better. In a flurry of theoretical activity, by James and collaborators (26,27) amongst others, the Durham k_{t} algorithm was firmly established as a new standard for jet physics.

The top quark and Higgs boson production

James made important contributions to the physics of the top quark long before its actual discovery at Fermilab in 1995. Shortly after his arrival in Durham, he and Ronald Kleiss used their helicity amplitude method to derive compact leading-order formulae for the combined production and decay of top–antitop pairs at hadron colliders, including full spin correlations and effects of the finite top lifetime (18). With Alan Martin, they used these for the most detailed survey to date of strategies for top quark discovery (15). Unfortunately the range of top masses covered ended at 120 GeV/c^2, as nobody then foresaw the true mass of 175 GeV/c^2, but the Kleiss–Stirling formulae remain in frequent use. Later, just in time for the top discovery, with Lynn Orr and Tim Stelzer he completed the corresponding calculation with an extra jet in the final state (31). Stelzer and his collaborators had implemented the Kleiss–Stirling helicity method in their program MadGraph, making computation of the 312 contributing Feynman diagrams feasible. MadGraph went on to become the leading tool for automatic computation of particle physics processes within and beyond the SM (Alwall *et al.* 2011).

At the time of James' arrival in Durham, the best way to search for and discover the Higgs boson at the proposed proton–proton high-energy colliders was a central problem in particle physics. Together with various collaborators, he made influential studies of Higgs production via vector boson fusion (12,16), as well as production in association with a vector boson (24) or a heavy quark pair (25). In all these papers, Higgs decay into two photons was emphasized as a clean signature, which was indeed the means of the 2012 discovery. The unforeseen large mass of the top quark means that the dominant production is via gluon fusion to form a virtual $t\bar{t}$ pair, but the other mechanisms studied by James over two decades earlier are nowadays essential ingredients in analyses of the LHC Higgs data.

Other research at Durham

In the 1970s, Fadin, Kuraev & Lipatov (1977) and Balitsky & Lipatov (1978) (BFKL) derived an equation for the high-energy behaviour of the scattering of hadronic objects within perturbative QCD. This naturally attracted James' attention. We mention just three of his contributions here. The equation sums low-energy gluon emissions to all orders in the leading logarithm approximation. It leads to a sharp rise in small-x deep-inelastic scattering. James addressed the problem of disentangling the BFKL perturbative QCD contribution from the non-perturbative component by comparing very forward and backward produced jets in the same event in hadron–hadron collisions (30). Later, with Lynne Orr, he refined the procedure paying particular attention to the azimuthal angle decorrelation of the jet pair (36). They significantly improved the 'BFKL' agreement with the experimental data. Besides the intrinsic interest, James, as was typical, was aware of the importance of these studies to experiment. So the precise knowledge of the transverse momentum distribution of the intermediate gluons was studied, which is a pre-condition to isolating new physics signals from the underlying event at hadron colliders (49).

With Alan Martin and Valery Khoze at Durham and Misha Ryskin in St Petersburg, James pioneered the study of Central Exclusive Production (CEP), a unique class of processes in which colliding hadrons produce an object of interest but crucially the hadrons remain intact after the collision (50,51). This work became part of a large collaboration to promote the study of such 'forward physics' processes at the LHC, making use of the information provided by dedicated 'proton tagging' detectors near the beam directions (56,68).

Yet another important activity to which James made significant contributions concerned the implications of data on processes in which a pair of W bosons were produced in experiments at high energy colliders. It was recognized that these processes were ideal to explore the presence of anomalous gauge boson couplings which would directly indicate the existence of new physics beyond the SM (40,41). A different aspect was the novel effects discovered near the threshold in WW production (29,32).

QCD and collider physics

In April 1996, Keith Ellis (FRS 2009), Bryan Webber and James completed their graduate text that became a standard reference known as ‘the pink book’ (33).[2] At the time it gave the most complete coverage of standard model physics as applied to collider processes, with special emphasis on QCD. The top quark had been discovered a year before, so all the components of the SM were in place except for the Higgs boson. This was the subject of the penultimate chapter, mostly written by James, which concentrated on strategies for Higgs discovery at the LHC and therefore remained relevant long after publication.

Foundation of the Institute for Particle Physics Phenomenology

2000 proved to be a pivotal year for James’ career. The Particle Physics and Astronomy Research Council had decided to close the particle theory group in the Rutherford Appleton Laboratory and to create an Institute for Particle Physics Phenomenology (IPPP) in a university. Twelve universities vied for the privilege. The Durham negotiating team (the Vice-Chancellor, Sir Ken Calman, Alan Martin, Mike Pennington and James—known locally as ‘the gang of four’) were able to present a particularly strong case. First, the Durham particle theory group had arranged an extremely successful series of phenomenology workshops in the 1990s. Second, the University offered to construct a new building (the Ogden Centre) and to create four new permanent Lectureships. Moreover, the case was presented by James with characteristic clarity and vision. Durham was awarded the IPPP, which was opened by the Prime Minister in 2002 (figure 4). James became its first Director and his exceptional administrative and organizational skills became evident for all to see.

Nigel Glover (FRS 2013) followed James as Director of the IPPP. At the Commemoration Service for James, held in Durham Cathedral in May 2019, the following quote from Nigel’s tribute beautifully expresses his legacy to the IPPP.

> James put all of his considerable energy into making the new IPPP a success. James’ intellectual brilliance, coupled with a very strong work ethic, and his softly spoken style helped him excel in that most difficult of tasks, academic leadership. As you would expect, he led the design of the new building, developed the research strategy, recruited the academic staff and so on and he achieved this in his inclusive and collegial way. There were setbacks and problems of course, but he never showed any frustration. He was always calm, positive and encouraging. On occasion, he would think quietly, polishing his pebble glasses for a few minutes, before coming up with a creative, decisive and above all, sympathetic, solution. James created a great atmosphere in the Institute—scientifically of course, but particularly, socially, with annual trips to the Lake District and regular pizza parties. In typical style, he would be the last one at a party, making sure that everything was tidied away and shipshape. He cared about the small details as well as the bigger picture. The members of the IPPP loved and respected him. To celebrate his 50th birthday, they bought him the table football table that remains to this day in the IPPP. From his school days one of his passions was music, and now, aided and abetted by Mike Whalley and

[2] Actually the colour was described by Cambridge University Press as ‘episcopal purple’.

Figure 4. When Prime Minister Tony Blair opened the IPPP on 18 October 2002 it is thought that he was saying to the Director that finding the Higgs boson is an important part of government policy. (Online version in colour.)

> Gudi Moortgat-Pick, he established the IPPP Ceilidh Band. The band was a tremendous success—their set included reels, jigs, polkas and hornpipes and, it has to be said, quite a lot of beer and sweat. The band performed when the annual Supersymmetry conference was held in Durham in 2005—and that evening, James the brilliant but unassuming physicist, transformed into a star. When he eventually left Durham in 2008, the IPPP staff wanted to do something to mark his time here. After some persuading, he agreed that an annual lecture would be OK but only because he thought it would raise the profile of the IPPP. The Stirling Lecture became a regular event, and, no matter how busy he was, he would come back to Durham each year to see how the IPPP was getting on.

Wider influence

James was a humble and modest person. He had a reputation of always acquiring the fullest possible knowledge of the facts and his decisions were scrupulously fair. This together with his intellectual brilliance and diligence meant that his advisory and administrative services were in great demand. We list some of the more major duties that he performed. From 2001 to 2003, he served as the first Chair of the Particle Physics and Astronomy Research Council's Science Committee, its top-level advisory committee. He was Pro-Vice Chancellor for Research of Durham University from 2005 until he left for Cambridge in 2008. He was a member of the Physics Sub-Panel in two Research Assessment Exercises (2001 and 2008), being Deputy Chair on the second occasion. He was a member of the Council of the Royal Society in 2007–8. From 2009 he served on the Council of the Science and Technology Facilities Council.

In May 1999 in recognition of his contribution to particle physics research, James was elected to the Fellowship of the Royal Society. He was appointed a CBE in the 2006 New Year Honours list, for services to Science.

Jacksonian Professor at Cambridge

Upon his return to Cambridge in 2008, James threw his formidable energy and intellect back into research with a vengeance. He revived his old interest (13,42) in the process of double parton scattering (DPS), where more than one constituent from each colliding hadron participates. With his graduate student Jonathan Gaunt, he formulated the first set of double parton distribution function to incorporate scaling violation while satisfying necessary conservation laws (58). In (62) they laid the foundation for an ongoing more rigorous approach to DPS. Other papers such as (59) explored novel signatures of DPS at the LHC.

Together with another of his students, Lucian Harland-Lang, James renewed the collaboration with Khoze and Ryskin on central exclusive production, focusing first on the production of states that could serve as ‘standard candles’ with which to constrain the underlying theory for CEP, and lend robustness to the corresponding predictions for possible new states and the Higgs boson (60). To achieve this, they developed extensive simulation tools that were used directly in experimental analyses. They predicted that the CEP of the χ_c meson, observed at the Tevatron, should contain a richer combination of different spin states than was initially assumed (61); this was subsequently supported by LHCb data. They provided the first calculation of the CEP of light meson pairs through a novel and elegant combination of the CEP theoretical framework with other techniques (63). In (64) they demonstrated for the first time how CEP could be used to extract precise mass measurements on the production of possible new states that decay partially to invisible particles.

With a third Cambridge graduate student, Eleni Vryonidou, James made a thorough study (65) of the impact that data on W boson plus charm quark production could have on understanding of the strange quark PDF, which motivated measurements of this process at the LHC. They also investigated the polarization of W and Z bosons in a wide variety of SM processes (66), which provides another avenue in the search for possible deviations due to new physics.

James had returned to Cambridge with the declared intention of doing research rather than administration. However, as was always the case, his personal qualities and administrative skills made him a natural target for recruitment to positions of authority. This led to his appointment as Head of Department at the Cavendish in 2011. In that capacity he accelerated the slow progress on rebuilding the Department, with a successful project to deliver the Maxwell Centre, which was completed in 2015 and is now the centrepiece of the industrial strategy for Physical Sciences at West Cambridge. This led on to plans for rebuilding the remaining parts of the Laboratory on a nearby larger site. Construction is now well under way, with completion expected in 2022. On an everyday level, his style of calm, fair leadership fostered an atmosphere of cooperation amongst the research groups that had not always been so evident. He was very proud to have secured the Athena SWAN Gold gender equality award for the Department, taking a personal lead in order to embed the cultural change necessary. Sadly for Cambridge, after only two years as Head of Department he was lured away to a more elevated post at Imperial College. Before leaving, he secured the future of the high-energy theory group at the Cavendish through the appointment of an additional lecturer in that field.

Provost of Imperial College

In 2013 James was appointed as the first ever Provost of Imperial College, London. In this newly created post he was responsible for Imperial's core academic mission of education, research and innovation. His work on the College's institutional culture, gender equality, valuing all staff, animal research processes, reforming technology transfer and enhancing research grant mechanisms was widely regarded as transformational. Immediately upon appointment he set about improving the diversity of the staff, creating a new post, provost envoy for gender equality, and, later, an assistant provost for diversity and inclusion. By the time he left the post in early 2018, colleagues commented that the whole mood music had changed at Imperial; it had become a far more amenable place for women to work. As a result of his efforts on animal welfare, the College's Central Biomedical Services division became the first animal care facility within a UK university to receive prestigious recognition from the Association for Assessment and Accreditation of Laboratory Animal Care (AAALAC International).

In September 2018, James received Imperial's highest honour, an honorary doctorate of science, during the College's Commemoration Day celebrations in recognition of his outstanding contributions to physics and to the College. Speaking at the time, Professor Alice Gast, Imperial's President, said: 'James defined the role of Provost, not only for Imperial, but for the world. It was a privilege to learn from his graceful and insightful approach to leadership.'

Retirement

Two months before he was due to leave Imperial College, James was diagnosed with pancreatic cancer. He died five months later. For his numerous friends and colleagues around the world the news of his death so very soon after his retirement was a tremendous shock. To his beloved wife and soulmate, Paula, this was a most cruel blow. Their plans for a well-deserved retirement were dashed. In his final months James received much comfort and support from his greatly loved children Tom and Helena, and his adored grandchildren Verity, Justin, Grace and Flora.

James leaves his imprint in many places. His scientific contributions form part of the foundations supporting the standard model of particle physics. The structures and processes he established in Durham, Cambridge and Imperial, bear testimony to his intelligence and organizational skills. But his legacy runs much more deeply because of the immense human impact he had on the people he worked with. He genuinely cared about them and their problems, large or small. The world has lost a brilliant scientist and an outstanding human being.

Honours and awards

1978 Smith's Prize in Mathematics, University of Cambridge

1992 Fellow of the Institute of Physics
1993 SERC/PPARC Senior Fellowship
1997 Humboldt Research Award, Alexander von Humboldt-Stiftung
1999 Fellow of the Royal Society
2006 Commander of the Most Excellent Order of the British Empire (CBE)
2013 Honorary Fellow of Peterhouse, Cambridge
2018 Honorary Doctor of Science, Imperial College, London

Acknowledgements

We are grateful to many colleagues of James who sent summaries of their collaborative research with him, and in particular thank Nigel Glover and Robert Thorne for helpful advice. The portrait image is by Thomas Angus of Imperial College. Other photographs were provided by IPPP.

Author profiles

Alan Martin

Alan Martin FRS is Emeritus Professor in the Department of Physics and the Institute for Particle Physics Phenomenology at Durham University. After obtaining a PhD in Theoretical Physics from University College London in 1962, he took Research Associate positions at the University of Illinois and then at the Rutherford Laboratory before joining the staff at Durham University in 1964. He was Head of the Physics Department 1989–93 and has remained at Durham apart from leaves of absence at CERN, at the University of Wisconsin, at the Institute of Nuclear Physics in Krakow, and as an Erskine Fellow at the University of Canterbury in New Zealand. He is co-author of four text books on particle physics and numerous papers in scientific journals, of which 64 were with James in the period 1984–2013. As a collaborator, James was a continual inspiration and a delight; he was always seeking, and sharing insights into, a deeper understanding of the sub-atomic world.

Bryan Webber

Bryan Webber FRS is Emeritus Professor of Theoretical Physics at the Cavendish Laboratory, University of Cambridge, and Visiting Senior Scientist at the Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo. After graduating from Oxford, he obtained a PhD in experimental particle physics from the University of California at Berkeley. He then switched to theoretical physics as a post doc in the research group of Geoffrey Chew at Berkeley. In 1971 he returned to the UK, where he has remained at the Cavendish Laboratory apart from several extended leaves of absence at CERN. From 1973 until retiring in 2010 he was head of the Cavendish theoretical high-energy physics group. His main research contributions have been in jet physics and the computer simulation of high-energy collisions. He first collaborated with James Stirling when James was a Research Fellow at DAMTP in the 1970s, and thereafter they remained firm friends, occasional collaborators and amicable competitors on topics ranging from small x to jet physics. As already mentioned, together with Keith Ellis they co-authored the book *QCD and Collider Physics*.

References to other authors

Alwall, J., Herquet, M., Maltoni, F., Mattelaer, O. & Stelzer, T. 2011 MadGraph 5: going beyond. *J. High Energy Phys.* **1106**, 128. (doi:10.1007/JHEP06(2011)128)

Balitsky, I. I. & Lipatov, L. N. 1978 The Pomeranchuk singularity in quantum chromodynamics. *Sov. J. Nucl. Phys.* **28**, 822 [*Yad. Fiz.* **28** (1978) 1597].

Becher, T. & Neubert, M. 2011 Drell–Yan production at small *qT*, transverse parton distributions and the collinear anomaly. *Eur. Phys. J. C* **71**, 1665. (doi:10.1140/epjc/s10052-011-1665-7)

Bethke, S. *et al.* [JADE Collaboration] 1988 Experimental investigation of the energy dependence of the strong coupling strength. *Phys. Lett. B* **213**, 235–241. (doi:10.1016/0370-2693(88)91032-5)

Dokshitzer, Y. L., Diakonov, D. & Troian, S. I. 1980 Hard processes in quantum chromodynamics. *Phys. Rept.* **58**, 269–395. (doi:10.1016/0370-1573(80)90043-5)

Drell, S. D. & Yan, T. M. 1970 Massive lepton-pair production in hadron–hadron collisions at high energies. *Phys. Rev. Lett.* **25**, 316. Erratum: *Phys. Rev. Lett.* **25** (1970), 902. (doi:10.1103/PhysRevLett.25.316)

Kleiss, R. 1984 The cross-section for $e^+e^- \rightarrow e^+e^-e^+e^-$. *Nucl. Phys. B* **241**, 61–74. (doi:10.1016/0550-3213(84)90197-4)

Kuraev, E. A., Lipatov, L. N. & Fadin, V. S. 1977 The Pomeranchuk singularity in Nonabelian Gauge theories. *Sov. Phys. JETP* **45**, 199–204 [*Zh. Eksp. Teor. Fiz.* **72** (1977) 377–389].

Polkinghorne, J. C. 1976 The breaking of Bjorken scaling in the covariant parton model. *Nucl. Phys. B* **108**, 253–264. (doi:10.1016/0550-3213(76)90551-4)

STFC. 2017 Science and Technology Facilities Council Impact Report 2017, p. 20.

Bibliography

The following publications are referred to directly in the text. A full bibliography is available as electronic supplementary material at http://dx.doi.org/10.1098/rsbm.2019.0031

(1) 1978 The Drell–Yan conjecture in asymptotically free theories. *Nucl. Phys. B* **145**, 477–509. (doi:10.1016/0550-3213(78)90097-4)

(2) 1981 (With S. D. Ellis & N. Fleishon). Logarithmic approximations, quark form-factors and quantum chromodynamics. *Phys. Rev. D* **24**, 1386–1399. (doi:10.1103/PhysRevD.24.1386)

(3) (With S. D. Ellis). Quark form-factors and leading double logarithms in QCD. *Phys. Rev. D* **23**, 214.

(4) 1984 (With C. T. H. Davies). Nonleading corrections to the Drell–Yan cross-section at small transverse momentum. *Nucl. Phys. B* **244**, 337–348. (doi:10.1016/0550-3213(84)90316-X)

(5) 1985 (With C. T. H. Davies & B. R. Webber). Drell–Yan cross-sections at small transverse momentum. *Nucl. Phys. B* **256**, 413. [1,I.95(1984)].

(6) (With S. Geer). Jet activity associated with W and Z^0 production. *Phys. Lett. B* **152**, 373–379. (doi:10.1016/0370-2693(85)90514-3)

(7) (With R. Kleiss). Spinor techniques for calculating $p\overline{p} \rightarrow W^{\pm}/Z^0 +$ Jets. *Nucl. Phys. B* **262**, 235–262. (doi:10.1016/0550-3213(85)90285-8)

(8) (With S. D. Ellis & R. Kleiss). W's, Z's and Jets. *Phys. Lett. B* **154**, 435–440. (doi:10.1016/0370-2693(85)90425-3)

(9) (With R. Kleiss & S. D. Ellis). W^+W^- pair production in high-energy hadronic collisions: signal versus background. *Phys. Lett. B* **163**, 261–266. (doi:10.1016/0370-2693(85)90234-5)

(10) (With S. D. Ellis & R. Kleiss). Missing transverse energy events and the standard model. *Phys. Lett. B* **158**, 341–348. (doi:10.1016/0370-2693(85)91195-5)

(11) 1986 (With S. D. Ellis & R. Kleiss). Monojets in the standard model. *Phys. Lett. B* **167**, 464–470. (doi:10.1016/0370-2693(86)91302-X)

(12) 1987 (With R. N. Cahn, S. D. Ellis & R. Kleiss). Transverse momentum signatures for heavy Higgs bosons. *Phys. Rev. D* **35**, 1626. (doi:10.1103/PhysRevD.35.1626)

(13) (With F. Halzen & P. Hoyer). Evidence for multiple parton interactions from the observation of multi-muon events in Drell–Yan experiments. *Phys. Lett. B* **188**, 375–378. (doi:10.1016/0370-2693(87)91400-6)

(14) (With A. D. Martin & R. G. Roberts). On the determination of limits on the number of light neutrinos and the top quark mass from *W*, *Z* production in $p\overline{p}$ collisions. *Phys. Lett. B* **189**, 220–225. (doi:10.1016/0370-2693(87)91300-1)

(15) 1988 (With R. Kleiss & A. D. Martin). The search for top quarks at hadron colliders: a realistic appraisal. *Z. Phys. C* **39**, 393–398. (doi:10.1007/BF01548290)

(16) (With R. Kleiss). Tagging the Higgs. *Phys. Lett. B* **200**, 193–199. (doi:10.1016/0370-2693(88)91135-5)

(17) (With A. D. Martin & R. G. Roberts). Structure function analysis and ψ, jet, W, Z production: pinning down the gluon. *Phys. Rev. D* **37**, 1161. (doi:10.1103/PhysRevD.37.1161)

(18) (With R. Kleiss). Top quark production at hadron colliders: some useful formulae. *Z. Phys. C* **40**, 419–423. (doi:10.1007/BF01548856)

(19) (With A. D. Martin & R. G. Roberts). Implications of new deep inelastic scattering data for parton distributions. *Phys. Lett. B* **206**, 327–332. (doi:10.1016/0370-2693(88)91515-8)

(20) 1989 (With A. D. Martin & R. G. Roberts). Benchmark cross-sections for $p\overline{p}$ collisions at 1.8 Tev. *Z. Phys. C* **42**, 277–284. (doi:10.1007/BF01555868)

(21) 1990 (With N. Brown). Jet cross-sections at leading double logarithm in e^+e^- annihilation. *Phys. Lett. B* **252**, 657–662. (doi:10.1016/0370-2693(90)90502-W)

(22) (With P. N. Harriman, A. D. Martin & R. G. Roberts). Parton distributions extracted from data on deep inelastic lepton scattering, prompt photon production and the Drell–Yan process. *Phys. Rev. D* **42**, 798–810. (doi:10.1103/physrevd.42.798)

(23) (With J. Kwiecinski, A. D. Martin & R. G. Roberts). Parton distributions at small *x*. *Phys. Rev. D* **42**, 3645–3659.

(24) 1991 (With R. Kleiss & Z. Kunszt). Discovering a light intermediate-mass Higgs in proton–proton collisions using associated production with *W* bosons. *Phys. Lett. B* **253**, 269–274. (doi:10.1016/0370-2693(91)91396-D)

(25) (With Z. Kunszt & Z. Trocsanyi). Clear signal of intermediate mass Higgs boson production at LHC and SSC. *Phys. Lett. B* **271**, 247–255. (doi:10.1016/0370-2693(91)91308-I)

(26) 1992 (With N. Brown). Finding jets and summing soft gluons: a new algorithm. *Z. Phys. C* **53**, 629–636. (doi:10.1007/BF01559740)

(27) (With S. Bethke, Z. Kunszt & D. E. Soper). New jet cluster algorithms: next-to-leading order QCD and hadronization corrections. *Nucl. Phys. B* **370**, 310–334. [Erratum: *Nucl. Phys. B* **523**, 681 (1998)]. (doi:10.1016/0550-3213(92)90289-N)

(28) (With P. J. Sutton, A. D. Martin & R. G. Roberts). Parton distributions for the pion extracted from Drell–Yan and prompt photon experiments. *Phys. Rev. D* **45**, 2349–2359. (doi:10.1103/physrevd.45.2349)

(29) 1993 (With Y. L. Dokshitzer, V. A. Khoze & L. H. Orr). Properties of soft radiation near $t\bar{t}$ and W^+W^- threshold. *Nucl. Phys. B* **403**, 65–100. (doi:10.1016/0550-3213(93)90029-O)

(30) 1994 Production of jet pairs at large relative rapidity in hadron–hadron collisions as a probe of the perturbative pomeron. *Nucl. Phys. B* **423**, 56–79. (doi:10.1016/0550-3213(94)90565-7)

(31) 1995 (With L. H. Orr & T. Stelzer). Gluon radiation in $t\bar{t}$ production at the Fermilab Tevatron $p\overline{p}$ collider. *Phys. Rev. D* **52**, 124–132. (doi:10.1103/PhysRevD.52.124)

(32) (With V. S. Fadin, V. A. Khoze & A. D. Martin). Higher order Coulomb corrections to the threshold $e^+e^- \rightarrow W^+W^-$ cross-section. *Phys. Lett. B* **363**, 112–117. (doi:10.1016/0370-2693(95)01194-U)

(33) 1996 (With R. K. Ellis & B. R. Webber). QCD and collider physics. *Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol.* **8**, 1–435.

(34) (With A. D. Martin & R. G. Roberts). Parton distributions: a study of the new HERA data, α_s, the gluon and *pp* jet production. *Phys. Lett. B* **387**, 419–426. (doi:10.1016/0370-2693(96)01031-3)

(35) (With T. Gehrmann). Polarized parton distributions in the nucleon. *Phys. Rev. D* **53**, 6100–6109. (doi:10.1103/PhysRevD.53.6100)

(36) 1997 (With Lynne H. Orr). Dijet production at hadron–hadron colliders in the BFKL approach. *Phys. Rev. D* **56**, 5875–5884. (doi:10.1103/PhysRevD.56.5875)

(37) 1998 (With A. D. Martin & R. G. Roberts). Parton distributions: a new global analysis. *Eur. Phys. J. C* **4**, 463–496. (doi:10.1007/s100529800904)

(38) (With A. D. Martin, R. G. Roberts & R. S. Thorne). Scheme dependence, leading order and higher twist studies of MRST partons. *Phys. Lett. B* **443**, 301–307. (doi:10.1016/S0370-2693(98)01325-2)

(39) 1999 (With A. Kulesza). Sudakov logarithm resummation in transverse momentum space for electroweak boson production at hadron colliders. *Nucl. Phys. B* **555**, 279–305. (doi:10.1016/S0550-3213(99)00298-9)

(40) (With A. Werthenbach). Anomalous quartic couplings in $\nu\nu\gamma\gamma$ production via WW-fusion at LEP-2. *Phys. Lett. B* **466**, 369–374. (doi:10.1016/S0370-2693(99)01165-X)

(41) 2000 (With A. Werthenbach). Anomalous quartic couplings in $W^+W^-\gamma$, $Z^0Z^0\gamma$ and $Z^0\gamma\gamma$ production at present and future e^+e^- colliders. *Eur. Phys. J. C* **14**, 103–110. (doi:10.1007/s100520000399)

(42) (With A. Kulesza). Like sign W boson production at the LHC as a probe of double parton scattering. *Phys. Lett. B* **475**, 168–175. (doi:10.1016/S0370-2693(99)01512-9)

(43) (With A. D. Martin, R. G. Roberts & R. S. Thorne). Parton distributions and the LHC: W and Z production. *Eur. Phys. J. C* **14**, 133–145. (doi:10.1007/s100520000324)

(44) (With A. D. Martin, R. G. Roberts & R. S. Thorne). Estimating the effect of NNLO contributions on global parton analyses. *Eur. Phys. J. C* **18**, 117–126. (doi:10.1007/s100520000529)

(45) 2002 (With A. D. Martin, R. G. Roberts & R. S. Thorne). MRST2001: partons and α_s from precise deep inelastic scattering and Tevatron jet data. *Eur. Phys. J. C* **23**, 73–87. (doi:10.1007/s100520100842)

(46) (With A. D. Martin, R. G. Roberts & R. S. Thorne). NNLO global parton analysis. *Phys. Lett. B* **531**, 216–224. (doi:10.1016/S0370-2693(02)01483-1)

(47) 2003 (With A. D. Martin, R. G. Roberts & R. S. Thorne). Uncertainties of predictions from parton distributions. I: Experimental errors. *Eur. Phys. J. C* **28**, 455–473. (doi:10.1140/epjc/s2003-01196-2)

(48) 2004 (With A. D. Martin, R. G. Roberts & R. S. Thorne). Uncertainties of predictions from parton distributions. II: Theoretical errors. *Eur. Phys. J. C* **35**, 325–348. (doi:10.1140/epjc/s2004-01825-2)

(49) (With V. A. Khoze, A. D. Martin & M. G. Ryskin). Spread of the gluon $\mathrm{k_t}$-distribution and the determination of the saturation scale at hadron colliders in the resummed next-to-leading logarithmic BFKL evolution. *Phys. Rev. D* **70**, 074013. (doi:10.1103/PhysRevD.70.074013)

(50) (With V. A. Khoze, A. D. Martin & M. G. Ryskin). Double diffractive chi meson production at the hadron colliders. *Eur. Phys. J. C* **35**, 211–220. (doi:10.1140/epjc/s2004-01857-6)

(51) 2005 (With V. A. Khoze, A. D. Martin & M. G. Ryskin). Diffractive $\gamma\gamma$ production at hadron colliders. *Eur. Phys. J. C* **38**, 475–482. (doi:10.1140/epjc/s2004-02059-0)

(52) (With A. D. Martin, R. G. Roberts & R. S. Thorne). Parton distributions incorporating QED contributions. *Eur. Phys. J. C* **39**, 155–161. (doi:10.1140/epjc/s2004-02088-7)

(53) 2007 (With A. D. Martin, R. S. Thorne & G. Watt). Update of parton distributions at NNLO. *Phys. Lett. B* **652**, 292–299. (doi:10.1016/j.physletb.2007.07.040)

(54) 2009 (With A. D. Martin, R. S. Thorne & G. Watt). Parton distributions for the LHC. *Eur. Phys. J. C* **63**, 189–285. (doi:10.1140/epjc/s10052-009-1072-5)

(55) (With A. D. Martin, R. S. Thorne & G. Watt). Uncertainties on α_S in global PDF analyses and implications for predicted hadronic cross sections. *Eur. Phys. J. C* **64**, 653–680. (doi:10.1140/epjc/s10052-009-1164-2)

(56) (With M. G. Albrow *et al.*). The FP420 R&D project: Higgs and New Physics with forward protons at the LHC. *JINST* **4**, T10001. (doi:10.1088/1748-0221/4/10/T10001)

(57) 2010 (With A. D. Martin, R. S. Thorne & G. Watt). Heavy-quark mass dependence in global PDF analyses and 3- and 4-flavour parton distributions. *Eur. Phys. J. C* **70**, 51–72. (doi:10.1140/epjc/s10052-010-1462-8)

(58) (With J. R. Gaunt). Double parton distributions incorporating perturbative QCD evolution and momentum and quark number sum rules. *J. High Energy Phys.* **3**. (doi:10.1007/JHEP03(2010)005)

(59) (With J. R. Gaunt, C.-H. Kom & A. Kulesza). Same-sign W pair production as a probe of double parton scattering at the LHC. *Eur. Phys. J. C* **69**, 53–65. (doi:10.1140/epjc/s10052-010-1362-y)

(60) (With L. A. Harland-Lang, V. A. Khoze & M. G. Ryskin). Standard candle central exclusive processes at the Tevatron and LHC. *Eur. Phys. J. C* **69**, 179–199. (doi:10.1140/epjc/s10052-010-1404-5)

(61) (With L. A. Harland-Lang, V. A. Khoze & M. G. Ryskin). Central exclusive χ_c meson production at the Tevatron revisited. *Eur. Phys. J. C* **65**, 433–448. (doi:10.1140/epjc/s10052-009-1214-9)

(62) 2011 (With J. R. Gaunt). Double parton scattering singularity in one-loop integrals. *J. High Energy Phys.* **6**, 48. (doi:10.1007/JHEP06(2011)048)

(63) (With L. A. Harland-Lang, V. A. Khoze & M. G. Ryskin). Central exclusive meson pair production in the perturbative regime at hadron colliders. *Eur. Phys. J. C* **71**, 1714. (doi:10.1140/epjc/s10052-011-1714-2)

(64) 2012 (With L. A. Harland-Lang, V. A. Khoze & M. G. Ryskin). The phenomenology of central exclusive production at hadron colliders. *Eur. Phys. J. C* **72**, 2110. (doi:10.1140/epjc/s10052-012-2110-2)

(65) (With E. Vryonidou). Charm production in association with an electroweak gauge boson at the LHC. *Phys. Rev. Lett.* **109**, 082002. (doi:10.1103/PhysRevLett.109.082002)

(66) (With E. Vryonidou). Electroweak gauge boson polarisation at the LHC. *J. High Energy Phys.* **7**, 124. (doi:10.1007/JHEP07(2012)124)

(67) 2013 (With A. D. Martin, A. J. Th. M. Mathijssen, R. S. Thorne, B. J. A. Watt & G. Watt). Extended parameterisations for MSTW PDFs and their effect on lepton charge asymmetry from *W* decays. *Eur. Phys. J. C* **73**, 2318. (doi:10.1140/epjc/s10052-013-2318-9)

(68) 2016 (With K. Akiba *et al.* LHC Forward Physics. *J. Phys. G* **43**, 110201. (doi:10.1088/0954-3899/43/11/110201)