ESF Exploratory Workshop: Electroweak Radiative Corrections to Hadronic Observables at TeV Energies

11–15 September 2003, Grey College, University of Durham, UK

Scientific Organiser: Stefano Moretti

Administrative Secretary: Linda A Wilkinson

Scientific Report

Preliminaries

- The workshop web-page can be found at:

  `http://www.hep.phys.soton.ac.uk/~stefano/ESF/`

1 Executive Summary

The aim of this meeting was to discuss the relevance of electroweak (EW) radiative corrections to scattering processes taking place at particle accelerators such as Tevatron (at FNAL) and particularly the Large Hadron Collider (LHC, at CERN), in the light of the latest theoretical developments in the field of higher order EW effects at TeV energy scales. These had already been proven to be of extreme importance in the context of electron-positron annihilations (e.g., at proposed Linear Colliders, LCs) and the workshop organisers believed that there were good reasons to expect that they cannot be ignored at present and future hadron colliders even in quantities typically regarded as 'hadronic observables' (jet data, Drell-Yan, prompt-photon production, bottom- and top-quark production, etc.). In addition, a particular mention was made of the issue of non-trivial spin-induced parity-violating effects originating in the EW theory which have no counterpart in QCD and that can readily

be observed already at lower energy hadronic colliders such as RHIC-Spin (at BNL), whose analysis turns out to be important for the understanding of higher energy hadronic data.

The scientific case made for the organisation of the workshop was as follows. The energy frontier of the present and future generation of particle physics accelerators is the TeV regime. At such energies, much larger than the EW scale, higher order EW effects can lead to big corrections, of several tens of percent. In jet processes, they can even be competitive with QCD corrections. The former are in fact driven by double logarithms that do not always cancel in inclusive quantities, unlike in the latter case. The investigation of these effects has only just started at the theoretical level. It is clear that further studies, also on the experimental side, are required, in order to bring such EW effects under control, thus enabling one to profitably analyse hadronic data also at future colliders. The main scope of this workshop was to bring together experts from the QCD and EW communities, both theorists and experimenters, with the aim, on the one hand, of identifying those hadronic processes where a joint effort is needed in order to make further progress in our understanding of forthcoming data and, on the other hand, of establishing long-term collaborations that will address the task of finding appropriate solutions, in step with the ongoing preparation studies for present and future accelerators. These should not only include the proton-antiproton Tevatron machine and the proton-proton LHC, but also the much lower energy RHIC-Spin machine, a polarised proton-proton collider (among other possible beam setups). Finally results already obtained in the context of a future electron-positron LC, also in presence of beam polarisation, would also serve as a guidance for the hadronic studies.

The meeting took place between Grey College, one of the Colleges of Durham University, and the Institute for Particle Physics Phenomenology (IPPP) at the newly-built Ogden Centre for Fundamental Physics, during the dates 11–15 September 2003. The workshop saw the participation of delegates from several European countries as well as Argentina, Japan and USA (as detailed below). Most gave presentations according to the programme referred to below and several formal and informal discussions took place, in order to assess the relevance of the topics discussed. Both theorists and experimenters were present, the latter in representation of the major experiments engaged at the above mentioned accelerators. It was agreed that the scientific case is pressing and that an ESF Scientific Network is the ideal framework in which establishing the collaborations needed to carry out the tasks outlined. It was also suggested that the scientific organiser of the workshop should also be the coordinator of the ESF Scientific Network and the one writing the proposal. Dr Moretti

has accepted this charge and set out to prepare an application for the forthcoming deadline of 1 May 2004. Finally, many of the participants were unaware of the possibilities offered by the ESF in terms of grants and they much enjoyed Prof. Judith Howard's presentation illustrating the opportunities in this context. In this respect, there was also discussion of the possibility of eventually considering applications to other ESF schemes to further sustain the research efforts on the mentioned topics as well as on others that emerged during the meeting. In general, both the extent of the ESF remit and its organisational structure were much appreciated by the delegates and thought of as an attractive alternative to the highly sophisticated schemes offered by the European Union through its Framework Programmes.

The workshop per se was very successful. From the feedback received from the participants both during and after the event, the main reason of success was the excellent quality of the presentations, the worldwide representation of the delegates that provided a global perspective of the current status of studies in the field, as well as the format, which encouraged very useful informal discussions even outside the scientific sessions (all participants were hosted in the same college and were having meals together). The IPPP proved to be an excellent host, both in terms of secretarial organisation and technical support provided. It truly was a meeting which helped to put the basis of long-term Europe-based collaborations at the cutting edge of particle physics research.

2 Scientific Content of the Event

Dr Dittmar (ETH) gave an overview of the potential accuracies for cross section measurements within CMS, one of the two multipurpose experiments which will be based at the CERN LHC (2007 onwards). He emphasised the need to control theoretical error at the percent level, through the understanding of higher order effects both in QCD and in the EW theory. This is not only relevant in view of tests of the Standard Model (SM), but also in the context of searches for new physics signals, which may emerge as small deviations from the SM expectations. Dr Tapprogge (HIP, Helsinki) gave a similar review for the case of the other multipurpose LHC experiment, ATLAS, illustrating in particular several examples of physics studies beyond the SM (such as, extended Higgs models and Supersymmetry) which require full understanding of the SM background in higher orders. Both talks made clear that the level of precision expected within the two experiments in the measurement of hadronic data is competitive with the size of the corrections expected from both next-to-next-to-leading

order (NNLO) QCD and NLO EW effects. Prof Huston (IPPP) took the charge of illustrating the physics potential of both the experiments now running at the Tevatron, CDF and D0. The physics topics addressed were very similar to those discussed by the two previous speakers. However, the context is different: a proton-antiproton machine at 2 TeV (Tevatron) as opposed to a proton-proton one at 14 TeV (LHC), so that the requirements imposed by the expected precision of the experimental measurements on the theory predictions bear a different emphasis. While in general one should expect NNLO QCD effects to dominate NLO EW ones, at least in inclusive quantities, because of the lower energy scale at which particle scatterings take place, it was emphasised that the asymmetric beam configuration would allow for the straightforward definition of asymmetries that may be sensitive to new physics (e.g., forward-backward asymmetries of leptons and b, t-quarks) and also subject to possibly large EW effects, while corresponding QCD corrections are normally under control.

The next talk was a theoretical one, by Stirling (IPPP), concerning the effects of higher order EW corrections in Parton Distribution Function (PDF) fits and in the evolution of partons inside the (anti)proton. In fact, due to the current lack of a general formalism to deal with purely weak effects in the partonic evolution equations, the talk was only concerned with electromagnetic (EM) effects. As for the latter, though they become relevant at the 1% level for large x and Q^2, their impact is still negligible compared to the current PDF uncertainties related to the treatment of the experimental data in doing the fits, the approximations adopted in the QCD evolution, the value of the strong coupling constant, etc. Once NNLO QCD PDFs become available, presumably the issue ought to be revisited. In this context, it was emphasised that there is a need for consistency in including EW effects in observables used in global fits, to avoid, e.g., double counting of photon radiation.

Dr De Florian (Buenos Aires) illustrated the physics potential of RHIC-Spin, with particular emphasis on the determination of polarised PDFs and the measurement of spin asymmetries, which – apart from helping the understanding of the spin content of the proton – could also shed light on the possible existence of new physics (e.g., extra gauge bosons, compositness) well ahead of the LHC and a LC. Unfortunately, the experimental setup and the foreseen machine programme are not yet finalised, so that achievable experimental accuracies cannot yet be foreseen confidently. The situation should however become clear in the course of this year.

Prof Glover (IPPP) recapped the current situation regarding the status of theoretical computation of NNLO QCD effects and made the point that in many physics contexts it is

the lack of their knowledge that prevents the underlying model to be tested beyond the 10% level or so, as the precision of measurements of many hadronic data is dominated by the theoretical error. The progress in tackling such computations has been tremendous in the last few years, so that one should expect actual predictions through the mentioned accuracy over the one-year time scale.

Dr Laenen (Nikhef) gave an overview of resummation calculations for hadronic quantities and of the techniques available, emphasising the need of going beyond the small-x limit currently studied. Resummation effects are important in most hadronic observables (e.g., Drell-Yan, Higgs production). However, they are mostly sizable at small transverse momentum, thus in a complementary dominion with respect to those induced by weak corrections in general, which typically onset at large transverse momentum.

Prof Kunszt (ETH) reminded the audience of the activities carried out within the EW Working Group (WG) in the context of the 1999 CERN Workshop on 'Standard Model Physics (and more) at the LHC', of which he was one of the conveners. He confirmed the necessity of further progress in the computation of both QCD and EW effects in perturbation theory, with a particular view on understanding the mechanism of Electroweak Symmetry Breaking (EWSB), though the detection of one or more Higgs bosons.

Dr Ciafaloni (Lecce) discussed at length the mechanism generating the large (Sudakov) logarithmic EW corrections referred to previously, describing several experimental consequences. He based his talk on known results stemming from the study of electron-positron annihilations at the TeV scale, yet he concluded that – despite a subtle cancellation mechanism of such logarithms exists in the case of hadronic collisions – the latter is only partial, thereby stressing the importance of the topics addressed by the workshop.

Prof Kühn (Karlsruhe) elaborated further on Sudakov logarithms, detailing the techniques available for their computation and reviewing several theoretical results for the case TeV scale electron-positron collisions, in the same final states that will thoroughly be studied also in the hadronic context (e.g., bottom- and top-quark production). He further discussed the source of universal as well as non-universal Sudakov logarithms and their power behaviour in such observables. He finally pointed out that most of the current computational techniques can indeed be transferred to the case of hadronic collisions.

Prof. Verzegnassi (Trieste) extended the scope of the previous two talks into the framework of the Minimal Supersymmetric Standard Model (MSSM), by considering the additional effects that may arise (e.g., in b-quark cross sections) due to the additional Supersymmetric

(SUSY) particles entering at loop-level. He emphasised that a clear pattern emerged for the structure of the logarithmic corrections in the MSSM and stated the importance of studying such effects also in the context of hadronic machines as well, where the energy available may further enhance typical SUSY effects.

Dr Belanger (Annecy) reported on several calculations of full one-loop EW corrections to single Higgs production channels at future LCs, discussing in the detail the separated effect of EM and weak corrections and showing that both affect the leading production modes of Higgs bosons at a level comparable with the expected experimental precisions at such machines.

Prof Ross (Southampton) discussed the effects of purely weak effects (limitedly to the case of processes with external gluons) in spin asymmetries at RHIC-Spin, emphasising that they enter hadronic cross sections at a rate comparable or larger than the differences expected between different sets of polarised PDFs and that they significantly affect observables sensitive to new physics effects. They may also offer the possibility of measuring the least constrained polarised PDF, that of the gluon, in parity-violating spin asymmetries, which are dominated at tree-level by quark scattering. Dr. Maina (Torino) addressed the case of $\gamma/Z+$ jet production through full one-loop level in presence of full one-loop weak effects at RHIC-Spin, Tevatron and LHC. He showed that the corresponding cross sections are affected by weak corrections which grow with energy, reaching the 10% level or more at the LHC, particularly at high transverse momentum, where the effects of both NLO and NNLO QCD is well under control. This result was considered very important by the audience at large, because γ/Z production (and their decay into leptons) is indeed 'the' precision observable at hadron colliders. Dr Pozzorini made the point that, even in pair production of gauge bosons (like WZ and $W\gamma$) at the LHC, EW effects (in this case evaluated at leading and next-to-leading logarithmic one- and two-loop level) can be very large, of order 20% at high transverse momentum. Gauge-boson pair production is used to investigate possible deviations of triple gauge-boson couplings from the SM value and the signatures expected are similar to the effects caused by pure SM effects like those mentioned. Dr Wackeroth (Buffalo) concluded the review on EW effects on gauge-boson production at hadron machines by presenting old and new results for W and Z hadro-production (at zero transverse momentum), discussing their impact in the measurement of the gauge-boson masses and widths, which are crucial parameters to test the self-consistency of the SM. Dr Carloni Calame (Pavia) discussed a similar problem with an emphasis on the case of real photon radiation, which can be the

source of sizable mass shifts in differential distribution reconstructing the W and Z gauge-boson masses in hadronic collisions. Mr Nolten (Southampton) discussed the effects of full one-loop weak corrections to the $b\bar{b}$ cross sections at Tevatron and the LHC, showing that the latter are negligible in inclusive rates yet sizable and comparable with full one-loop QCD effects in the forward-backward asymmetry, albeit with a different sign and structure.

Dr Burrows (Queen Mary) gave a review of the status of LC studies for hadronic observable in electron-positron annihilation, not only at very high energy (500–800 GeV), but also at the M_Z pole in presence of high luminosity, as foreseen in the context of the physics programme of future LCs (the so-called GigaZ option). The experimental precision (accounting for both systematics and statistics) is expected to be at the permille level or even less (e.g., in shape variables and jet rates used for the determination of the strong coupling constant, α_s). Hence, not only the knowledge of NNLO QCD is mandatory at LCs, but also that of NLO EW effects. In fact, this was confirmed by Dr Moretti (Southampton), who showed results for three-jet events (the leading contribution to any quantity dependent on α_s) at GigaZ, in presence of full one-loop weak effects, the latter contributing at the level of 2% or more, with a peculiar dependence on the quark flavour entering the multi-jet sample (because of the top-quark in the loops).

Dr Dittmaier (MPI) presented a review on (semi-)analytical tools available to perform one-loop computation for a generic number of external particles, massless or massive, describing in detail the various techniques and emphasising the scope for improvement in the future years. Dr Kurihara (KEK) illustrated instead similar progress in the case of numerical evaluations of one-loop amplitudes, detailing in particular the implementation of the GRACE program. Prof Jadach (Warsaw) concluded the session on tools for EW physics by reporting the needs that emerged in this respect from the activities of the corresponding WG of the recent workshop 'Monte Carlo for LHC', held at CERN in July 2003, stressing the importance of combining QCD and EW calculations in the same program, as is currently being done for Tevatron.

Prof Dixon (SLAC) discussed resonance-continuum interference effects in the di-photon Higgs signal at the LHC, the key channel to identify such a particle when its mass corresponds to the best fit to the precision data from Tevatron, SLC and LEP. This was a neat example in which QCD and EW effects concurs in a physics context crucial to the physics programme of a world machine, whose main task is to identify the mechanism of EWSB, which in the SM entails the presence of scalar particle, indeed the Higgs boson H. Dr Krämer (Edinburgh)

presented the results of EW radiative corrections to associated ZH and WH at hadron colliders, stressing that such effects are sizable particularly at the LHC, up to 10% (for $M_H \lesssim 130$ GeV), hence larger that the residual uncertainty of the corresponding NNLO QCD predictions due to their scale dependence (which is instead minimal in the EW theory). Finally, Dr Weiglein (IPPP) discussed loop effects in MSSM Higgs physics and their impact in phenomenological studies at hadron colliders, stressing the importance of establishing not only (small) deviations between the SM and the MSSM via precision measurements but also probe SUSY loop (including SUSY-EW loop) effects which quite dramatically change the Higgs phenomenology, for instance a large suppression of $gg \to h$, or $h \to b\bar{b}$ and $h \to \tau^+\tau^-$ (all key channels for MSSM Higgs detection at the LHC of a light SUSY Higgs state, h).

Whether scheduled or not, each half-day session was inevitably followed by lively discussions, generating an exchange of information which was one of the crucial ingredients of the success of the workshop.

3 Assessment of the Results

Several results were presented during the course of the meeting which made clear the need of establishing a synergy between the expertise existing in the two fields of QCD and EW physics and which was represented prior to the workshop by two rather different communities, not only on the theoretical but also on the experimental side, with little cross-fertilisation. It is only through the interaction between their representatives that progress can be made on the topics discussed above. It was a pleasure for the organisers to notice that such need was recognised by both communities, which enthusiastically embraced the prospect of establishing long-term collaborations. Effectively, issues that had previously rarely acquired the status of interdisciplinarity and the level of coordination between the QCD and EW physics sides that it is now clear they require, are now on the agenda of a blended community, which is represented (between participants and their collaborators) by well over 100 active researchers, mostly based in Europe. This number clearly represents a critical mass to guarantee progress in the field in the years to come. This is by far the most important outcome that this exploratory workshop has achieved, which is reflected in the eagerness of the participants to applying to the ESF for further funding under several schemes.

4 Final List of Participants

Locals	Europeans
1) Prof EW Nigel Glover[a]	10) Dr Genevieve Belanger[b]
2) Dr Gudrun Heinrich[a]	11) Dr Philip Burrows[c]
3) Prof Joey Huston[a]	12) Dr Carlo Carloni Calame[d]
4) Prod Valery A Khoze[a]	13) Dr Paolo Ciafaloni[e]
5) Dr Gudrid Moortgat-Pick[a]	14) Dr Stefan Dittmaier[f]
6) Dr Carlo Oleari[a]	15) Dr Michael Dittmar[g]
7) Prof Costas Papadopoulos[a]	16) Prof Wolfang Hollik[f]
8) Prof W James Stirling[a]	17) Prof Stanislaw Jadach[h]
9) Dr Georg Weiglein[a]	18) Dr Michael Kraemer[i]
	19) Prof Zoltan Kunszt[g]
	20) Prof J Hans Kühn[j]
	21) Dr Eric Laenen[k]
	22) Dr Ezio Maina[l]
	23) Dr Stefano Moretti[m]
	24) Mr Martin R Nolten[m]
	25) Dr Stefano Pozzorini[j]
	26) Prof Douglas A Ross[m]
	27) Dr Markus Roth[j]
	28) Dr Stefan Tapprogge[n]
	29) Prof Claudio Verzegnassi[o]

Overseas
30) Dr Daniel de Florian[p]
31) Prof Lance Dixon[q]
32) Dr Yoshimasa Kurihara[r]
33) Dr Doreen Wackeroth[s]

Workshop secretary: Mrs Linda A Wilkinson[a]

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- Email addresses can be found at:

`http://www.hep.phys.soton.ac.uk/~stefano/ESF/participants.html`

5 Final Programme

This can be found at:

`http://www.hep.phys.soton.ac.uk/~stefano/ESF/programme.html`

6 Statistical Information on the Participants

There were 33 participants to the workshop, excluding the secretary and the ESF representative: see

`http://www.hep.phys.soton.ac.uk/~stefano/ESF/participants.html`

Nine of these were locals. Of the others, one is based in Argentina, one in Japan and two in USA, with the remaining ones coming from Europe. The country representation (defined as how many people were regularly based in a given country at the time of the workshop) is as follows:

Country	Number of Representatives*
UK	13: **********
Germany	5: *****
Italy	4: ****
Switzerland	2: **
Finland	1: *
France	1: *
Greece†	1: *
Poland	1: *
The Netherlands	1: *
USA	2: **
Japan	1: *
Argentina	1: *

(*The large UK representation here is clearly biased by the presence of locals, who participated in the workshop sessions. †Prof Papadopoulos appeared on the web-pages with UK affiliation as he is visiting professor to the IPPP, where he was at the time of the meeting, although he is normally based in Greece.)

The (approximate) age structure was as follows:

Age Group	Number of Representatives*
≤ 30	3: ***
$30-40$	15: ***************
$40-50$	8: ********
$50-60$	6: ******
≥ 60	1: *

*Compatibly with the level of expertise required by the topics addressed by the workshop, an effort was made by the organisers to invite people in younger age groups.