Past and present research

W-pair production in e^+e^- collisions:

- **on shell:** during the 1990's an important part of my research was concentrated around the process $e^+e^- \to W^+W^-$. The complete $\mathcal{O}(\alpha)$ radiative corrections were calculated in [30, 39, 41], involving virtual corrections and soft- as well as hard-photon effects. In addition the influence of higher-order QED corrections was studied in [39] to give reliable predictions for the on-shell process close to the production threshold (LEP2). Also the production of W bosons at high energies ($\gtrsim$ 500 GeV) was considered, since this reaction is a prime candidate for studying the non-abelian triple-gauge-boson couplings at a high-energy linear electron–positron collider (LC). The status of the Standard-Model (SM) predictions and the problems typical for these high energies were discussed in [8, 9, 15, 17]. In particular the effects related to the resummation of 1PI $\mathcal{O}(\alpha)$ fermion-loop corrections, important in view of issues like unitarity cancellations and gauge invariance, were investigated in [14], and an effective high-energy approximation for W-pair production was constructed in [16, 46, 48]. These studies revealed the presence of large logarithmic corrections associated with weak loops and sizeable top-quark effects as a result of the unitarity cancellations or the absence thereof (delayed unitarity).

- **off shell, $e^+e^- \to 4f$:** the impact of the long-range Coulombic force on the total cross-section near threshold and on the determination of the W mass was investigated in [49]. This involved a study of the various screening phenomena, like the W decay and the off-shellness of the W bosons, which effectively truncate the range of the Coulomb interaction and hence reduce the size of the corresponding corrections. In a similar way the influence of the Yukawa interaction, mediated by the Higgs boson, was analyzed in [56]. In [21, 22, 53, 60] the long-standing problem of a gauge-invariant treatment of unstable gauge bosons was addressed. The implementation of the finite decay widths of these unstable particles involves the resummation of self-energy effects. This procedure mixes different orders of perturbation theory and thereby jeopardizes gauge invariance. At LEP2 and LC energies this violation of gauge invariance proved catastrophic, leading to completely wrong theoretical predictions. Based on the work presented in [14], a method was developed to arrive at a reliable, gauge-invariant implementation of the finite-width effects in the (lowest-order) Monte Carlo generators for $e^+e^- \to 2f$, $2f\gamma$, $4f$, $\cdots$. This method involves only taking into account the fermionic degrees of freedom, motivated by the observation that the W (and Z) bosons decay exclusively into fermions at lowest order. The issue of how to define the mass of an unstable boson if the decay width is very large was studied in [54]. The same study also revealed that the complex particle poles as well as the peak-positions of the associated resonance shapes are bounded, whatever the size of the width. This conclusion was reached without making the usual assumptions on the breakdown of perturbation theory. Recently a completely novel (non-diagrammatic) technique was developed for treating general unstable particles [69, 74]. By using a gauge-invariant effective-action approach, we have succeeded in generating the self-energy effects in the propagators whilst preserving gauge invariance through non-local multi-particle interactions. During the period 1995 – 1999 I supervised a Ph.D. student at the University of Leiden on the topic of the interplay between the radiative (quantum) corrections of the electroweak theory and the resonance description of the gauge bosons. This project culminated in a comprehensive paper on the various subtle effects that play a role in this context [66] (see also [6, 27]). The fact that the intermediate gauge bosons are unstable particles, for instance, gives rise to novel QED final-state interference effects, connecting the two decaying gauge-boson systems. This technically demanding topic was addressed in [61, 62, 25], where also the impact on the W-boson analysis at LEP2 (and the LC) was assessed. On top of that, we came across an overlooked effect that strongly affects the experimental determination of the W-boson mass [65]. It involves the interplay between electromagnetic radiation from the final-state particles and the experimental definition of the invariant-mass distribution that should describe the unstable intermediate gauge boson. We found that the distortion of the invariant-mass distribution by the final-state radiation can take on sizeable proportions.

- **general:** the above studies culminated in a review on W-pair physics, written in collaboration with A. Denner [76], and in various working-group reports for the LC [8, 9, 77] and LEP2 [10]. A survey of the various aspects of W-boson physics at high-energy linear colliders was given in [23].

Heavy-fermion-pair production in e^+e^- collisions: in [1, 11, 40, 42, 75] the radiative corrections to heavy-fermion-pair production and in particular to top-pair production were studied in a wide range of energies. Especially the influence of the unknown SM parameters (at that time: m_{t} and M_{H}) was analyzed. In top-pair production these parameters can be studied most efficiently at the $\mathrm{t\bar{t}}$ production threshold. In [42] the influence of Higgs-boson corrections at the production threshold of (heavy) top quarks was investigated. This analysis showed a strong sensitivity to M_{H} if the Higgs boson is light. In [44] the effects of the parameters of the two Higgs-doublet extension of the SM were assessed for $\mathrm{t\bar{t}}$ production near threshold and at high energies.

Higher-order QED corrections in leading-log approximation: in [12] the most general formalism was studied to compute the large logarithmic terms appearing in the QED radiative corrections to various processes. Being related to collinear divergences, these terms are controlled by the renormalization-group equations and can be calculated by means of the structure-function method, a strategy taken over from QCD. In [12] and [36] the structure-function method was used to calculate a subset of leading QED corrections to multi-differential cross-sections. This subset comprises $\mathcal{O}(\alpha) + \mathcal{O}(\alpha^2)$ QED corrections that are leading in the large logarithms (the so-called leading logs) and an exponentiation of the corresponding soft-photon corrections. Leading-log calculations of this type were performed for the forward–backward asymmetry [12, 37], for Bhabha scattering at large and small angles including cuts on the final-state particles [36, 38, 43, 45], for near-threshold Z- and

W-pair production in the zero-width approximation [12, 39], and for W-pair production at high energies [39]. Combined with exact $\mathcal{O}(\alpha)$ calculations these higher-order leading-log evaluations yield excellent theoretical predictions. Moreover, they provide powerful checks of exact calculations.

Z physics: another substantial part of my research during the 1990's was devoted to LEP1/SLC Z physics. In [31] the $\mathcal{O}(\alpha)$ corrections to the Z-boson partial widths were investigated, being of crucial importance for discriminating between SM predictions and possible signs of new physics. In [2, 4, 34] various aspects of the (weak/QED/QCD) radiative corrections to the Z line shape, as given by the total cross-section for light-fermion-pair production in e^+e^- annihilation, were analyzed. For instance, approximate expressions and simple rules of thumb were presented, giving insight into the effects accumulating to the SM prediction for the shape of the Z resonance. The weak corrections to the LEP1/SLC asymmetries were evaluated in [75], whereas higher-order leading-log-improved calculations of the forward–backward asymmetry were given in [3, 12, 37]. In [18, 36, 38, 43, 45] the calculations of QED corrections to Bhabha scattering at large and small angles were brought at a level of theoretical accuracy comparable to that of the other fermionic final states. This was of crucial importance to universality studies, common lepton analyses, and the determination of the luminosity. As to the latter, an assessment was given of the ingredients that would be necessary in order to meet the 0.1% precision of the improved high-statistics luminosity detectors at LEP. The status of the theoretical predictions for large-angle Bhabha scattering was surveyed in [13] and [63].

Large logarithms in electroweak processes at high energies: by the turn of the millennium a project was started that involved the systematic study of the large logarithmic effects that dominate the high-energy behaviour of electroweak processes. A proper understanding of these surprisingly large electroweak corrections is crucial for an accurate description of reactions in the envisaged energy-range of the LC. On this topic I supervised a Ph.D. student at the University of Durham (England) during the period 1999 – 2000. A special formalism was developed in [7, 28, 29, 70, 72] for calculating the dominant double-logarithmic effects, the so-called Sudakov logarithms, for arbitrary electroweak processes. By means of an explicit $\mathcal{O}(\alpha^2)$ calculation, a controversy in the literature concerning the perturbative structure of these Sudakov logarithms was settled in [70] and [72]. To this end it was identified to what extent the electroweak theory, with its multitude of mass scales owing to the mass-generation mechanism, behaves like an unbroken (massless) theory at high energies. In particular the investigation of the massive gauge-boson sector required special care in view of the presence of the longitudinal (massive) degrees of freedom.

Integral and projection techniques: in [33] and [75] new techniques were investigated for calculating the IR-divergent scalar and tensor integrals that appear in the evaluation of electroweak radiative corrections. Regarding the scalar integrals this involved, besides the usual techniques like Feynman parametrization, also the application of the Cutkosky cutting rule. The cutting rule was used in order to derive the absorptive part of the analytic function, which is subsequently combined with a (single) dispersion integral to arrive at the complete expression. By introducing projection methods one is able to derive in an elegant way how the IR-divergent scalar integrals enter the reduction of the tensor integrals. These projection methods can avoid the use of elaborate matrix-based reduction procedures that enhance possible numerical instabilities. Both techniques described above are suited for 4- as well as n-dimensional treatments.

Heavy-particle production in hadron−hadron collisions:

- **QCD, heavy quarks:** in [32] and [35] the $\mathcal{O}(\alpha_s)$ corrections to the hadroproduction of heavy quarks (e.g. $t\bar{t}$ production at the Tevatron) were calculated using perturbative QCD. A range of cross-sections and distributions was presented for the various initial states and the various hadron colliders. These $\mathcal{O}(\alpha_s)$ QCD corrections played an important role in extracting the presently quoted values for the top-quark mass. An analysis of the corresponding weak corrections was presented in [47]. The QCD final-state interference effects, connecting the two top-quark decay systems, were studied in [67], using the methods developed for the off-shell W-pair production process.

- **supersymmetric QCD, squarks and gluinos:** during the last ten years I have extended the scope of my research, by adding the more speculative element of supersymmetric (SUSY) phenomenology. In this context I supervised a Ph.D. student at DESY during the period 1993 − 1996 on the topic of hadroproduction (at the Tevatron/LHC) of squarks and gluinos, the SUSY partners of the quarks and gluons. Since lowest-order QCD predictions are notoriously imprecise, the full set of $\mathcal{O}(\alpha_s)$ corrections to the production and decay of these heavy SUSY particles is indispensable for coming up with stable and reliable predictions. These $\mathcal{O}(\alpha_s)$ SUSY-QCD corrections were studied in [5, 19, 20, 50, 52, 58, 59, 64] for the production and in [51, 55, 57] for the decays. As anticipated the corrections to the production cross-sections were found to be very large, sometimes as large as the lowest-order predictions themselves. Although at present squarks and gluinos are not yet discovered at the Tevatron, the $\mathcal{O}(\alpha_s)$ SUSY-QCD corrections are nevertheless important for extracting reliable exclusion limits from the data. If the squarks and gluinos were to be detected at the Tevatron or LHC, an accurate extraction of the corresponding masses has to take proper account of the radiative corrections. More recently this line of research was extended to the SUSY-electroweak sector [26, 68] in a study of $\mathcal{O}(\alpha_s)$ SUSY-QCD corrections to the production of colourless SUSY particles, i.e. the SUSY partners of the electroweak bosons and leptons.

- **QCD, associated production of Higgs bosons and heavy quarks:** the only remaining particle that is predicted by the Standard Model of electroweak interactions but has escaped detection up to now is the so-called Higgs boson, which occurs as a remnant of the mass-generation mechanism through spontaneous symmetry breaking. With the start of Run II at the proton−antiproton collider Tevatron, a new era of hadroproduction Higgs searches commenced in 2001. Since the Higgs boson couples to other particles with a strength proportional to the mass of those particles, one of the important hadroproduction search modes involves associated production of a Higgs boson and heavy quarks (e.g. top-quarks). In order to stabilize the theoretical predictions for this process, a project was started with the aim of determining the corresponding $\mathcal{O}(\alpha_s)$ corrections. The fact that two different masses enter the calculation and three heavy particles occur in the final state gave rise to various technical bottle-necks. Amongst other things, a dedicated novel technique was developed in [71] and [73] for dealing with so-called pentagon corrections, which involve simultaneously all five particles that take part in the process.

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