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PREFACE

In recent years quantum field theory has been very successful, not only critical respect but also popular success. However this book is not a systematic presentation of quantum field theory from first principles. In some degree it is a celebration of the fact that the theory agrees with the data and up to this day the numerical agreement is a solid fact.

From this point of view this book is somewhat unusual in that we discuss the structure of the perturbative expansion but viewing the theory in its true relation with precision experiments. There is every reason to believe that the Standard Model describes elementary processes with great accuracy. The sensitivity in radiative corrections allows precision tests at the level of the quantum structure and, therefore, they require the highest standards on the theoretical side. This book may be understood as concluding a certain period of theoretical development and providing a consensus about the present situation in the calculation of the precision observables and estimates of their theoretical errors. In summary, the book provides a basic documentation on the sizeable amount of theoretical work which has contributed to a steady improvement of the foundations and of the predictions of the $SU(3) \times SU(2) \times U(1)$ theory that finally shaped also during last decades.

Our approach begins with the Lagrangian of the Standard Model but the book is not a text on formal issues in perturbative field theory. On the contrary the aim is: to make it clear the course starting from the renormalizability of the theory and providing guidance for its applications to high energy phenomena. Our guideline has been to present all the details needed to derive the results and to collect in one place all relevant formulas, recipes and prescriptions which are needed to construct loop corrections and improvements in quantum field theory.

There is another aspect of the book that we consider to be rather peculiar: every derivation comes from two, or more, alternative structural frames. Instead of privileging one particular approach we decided to cover all aspects usually hidden in the choice of a renormalization scheme. It has been our care to avoid writing a book which is definitely bound to a very specific moment, although quite accidentally it was finished at the exact moment when the analysis of the LEP 1 data has come to the end (the 1998 Rochester Conference). This has been achieved by writing about first principles and by presenting a complete analysis of all aspects of renormalization and of loop corrections which could apply under any circumstance. The applications however, are mainly for energies of today although numerical results should have a relatively minor role.

The book is divided broadly into four parts. The first part, Chapters 2-3, develops radiative corrections in quantum electrodynamics, with the phenomenological inclusion of resonances. We have the almost unique opportunity of introducing and developing the concept of renormalization scheme in a somewhat simplified context. Loop corrections in QED are discussed, as well as the infrared problem. All relevant results concerning dimensional regularization of ultraviolet and infrared divergences are explained, the soft approximation and the hard bremmstrahlung corrections are introduced with emphasis on calculation. We have tried to indicate the origin of large effects in radiative corrections and their eventual re-summation, underlying the important aspects of renormalization group arguments.

In the second part, Chapters 4-6, we give an extended treatment on the foundation of loop calculus in renormalizable quantum field theory. Loop integrals and their reduction to scalar functions are extensively subjected to a critical evaluation and completely general results are shown for two-, three- and four-point functions. All known examples of special cases for scalar integrals are reported. After that we specialize to the minimal standard model and collect, in several chapters, the ensemble of self energies, vertices and box diagrams which contribute to create the most complete library of auxiliary functions in the field. That includes a complete description of the methods of calculation of one-loop corrections, polylogarithms and ways of computing them, running of coupling constants and masses, the widely used renormalization schemes – low-energy, on-shell, $\overline{MS}$, generalized minimal subtraction, complex mass.

Since we are dealing with a gauge theory, we have concentrated on the issue of gauge invariance. In order to emphasize the concept of gauge parameter independence we have developed a library of one loop diagrams within the general R_ξ-gauge with three independent parameters. This approach is not a matter of taste and we have organized the material so that the proof of gauge invariance of the renormalization equations, in any scheme, becomes almost automatic.

In deriving our formulae, we created many programs, written in FORM, for the semi-automatic, analytical computation of one loop Feynman diagrams. These programs generate diagrams, perform the relevant tensor-reduction to scalar integrals and allow for a sizeable compactification of the final results.

The third part, Chapters 7-13, deals with questions of renormalizability of the standard model and solves the problem of re-summing potentially large higher order corrections. This part follows a presentation in which all the results are derived in two, alternative, renormalization schemes, the non-minimal on mass shell scheme in the unitary gauge and the generalized minimal subtraction scheme in the renormalizable gauge. Applications are discussed to improved, one-loop, experimentally relevant decay widths and cross sections.

Finally, in the last part, Chapters 14-19, we undertake an extensive discussion of the theoretical aspects and of the phenomenological implications of e^+e^- annihilation above and far above the Z-resonance. There is again an emphasis on the issue of gauge invariance and on calculation. The last chapters deal with the basis for understanding of high energy annihilation, $e^+e^- \to$ two fermions and $e^+e^- \to$ four fermions. We present two issues that are very relevant for our understanding of the fundamental interactions: a precise measurement of the W-boson mass and the searches for the standard model Higgs boson. Although a large body of results is available for on shell vector boson production in e^+e^- annihilation, we have privileged the point of view that they are unstable particles and, therefore, the true final state contains four fermions. This approach should not be considered as a matter of taste, and radiative corrections to $e^+e^- \to W^+W^-, ZZ$ etc, are only a first approximation to the complete answer.

There are several sets of tables and figures within the text. For $e^+e^- \to f\overline{f}$, they have been produced with the help of two FORTRAN programs, TOPAZ0 and ZFITTER. The findings of most of the analyses performed during the last years are based on several semi-analytical computer codes. It is worth emphasizing that the design of some of these codes traces back to the 1989 Workshop on "Z-Physics at LEP1", while others have been developed later. All of them contain a so-called electroweak library which allows to calculate virtual higher order electroweak and QCD corrections to selected quantities. TOPAZ0 and ZFITTER are among those that contain, in addition, virtual and real photonic corrections (bremsstrahlung) with simple kinematical and geometrical cuts similar to those used in experiments thus allowing for the calculation of rather realistic (although still idealized) measurable cross sections and asymmetries. All the codes have been constantly updated till the 1998 Conferences. To the best of our knowledge however, TOPAZ0 and ZFITTER are, in May 1998, the only ones that have been updated to include $\mathcal{O}\left(\alpha^2\right)$ next-to-leading corrections. For $e^+e^- \to$ four fermions all numerical results are obtained with the FORTRAN code WTO.

The roots of this book are in the desire of developing the technology of precision electroweak calculations. The modern phase of this activity began in the late 1970's but since the starting of LEP experiments in 1989 several people working in the field have pooled their expertise to provide a solid and carefully cross-checked foundation for the measurements. Thus the origin of the book dates to the late 1970's but the most important events that contributed to create the review are the 1989 Workshop on "Z-Physics at LEP1", the 1995 Workshop "Reports of the working Group on Precision Calculations for the Z-resonance" and the 1996 Workshop on "Physics at LEP2". In this regard, we would like to thank all the members of the working groups for LEP1 and LEP2 physics.

A group of physicists has made this book possible through their encouragement at various critical stages. In the development of our work we had the unique opportunity of a day by day collaboration with many colleagues. It is also because of the continuous interaction with them that the book can now make its appearance. In particular we acknowledge many important discussions with Oreste Nicrosini, Guido Montagna and Fulvio Piccinini of the TOPAZ0 Collaboration and with Penka Christova, Mark Jack, Lida Kalinovskaya, Alexander Olshevski, Sabine Riemann and Tord Riemann of the ZFITTER Collaboration.

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A book in preparation is, often, something difficult to deal with. Our basic philosophy in writing it has been that, once a chapter is ready the question of who has done what is immediately forgotten, or better, buried with our conscience. Finally, in this book the Pauli metric has been used, $p^2 = -m^2$. We have some hope that this will not touch too many raw emotions.