Preface

It would be hard to persuade a new student beginning particle physics in 2007 that there once was a time when there was *not yet* a Standard Model. How else, would he object, could one explain all known features of strong, electro-magnetic and weak interactions? The absence of Flavour Changing Neutral Currents (FCNC), the universality of weak charged current interactions, the smallness of the $K^0 - \bar{K^0}$ mixing, the existence of the Δ^{++} resonance, the apparently infinitely rising neutrino cross-section, the $\Delta I = \frac{1}{2}$ rule in weak decays, the hadron spectroscopy respecting the eight-fold way, CP violation... How could you live for such a long time with all these problems without inventing the Standard Model which solves them all?

Of course, shall we older people answer, it took more than ten years from the original idea of the existence of the W boson [1] to the realization that an experimentally successful model with weak isospin symmetry [2] would imply the existence, not only of Neutral Weak Currents but also of charmed particles [3, 4], and a few more years for 't Hooft [5] to demonstrate that such a model would constitute a mathematical consistent theory. This we believe is the main answer to our student's surprise: the solution of the puzzle required i) two new experimental discoveries, that of Neutral Currents and that of Charm; and ii) a theoretical breakthrough, the renormalization of the Gauge Theory.

The dam broke in 1973 with the observation of Neutral Currents. The sequence of events that followed this discovery is really breathtaking: charm in 1974, tau lepton in 1975, beauty in 1977, direct observation of the W and Z bosons in 1983. The model was soon universally accepted, especially when more precise verifications of its quantitative predictions were made in atoms [6] and in electron nucleon scattering [7]. For the last 25 years the

THE PHYSICS OF THE *Z* AND *W* BOSONS

Model has met a long series of experimental verifications, proving itself an unbelievably successful scheme.

So successful the model is, that it would be perhaps even harder to persuade the aforementioned beginner physicist that a time could well come when there will be *no more* a Standard Model. Why should one abandon such a successful scheme, after all?

As a matter of fact, it has been argued by many respectable physicists that, although the Standard Model is in contradiction with no known experimental result in particle physics today, it certainly leaves several fundamental questions unanswered; among these, the fact that it requires as arbitrary input so many different particle masses. Also, the observed baryon-anti-baryon asymmetry in the Universe is very hard to explain within its framework. Furthermore, the role and the nature of the Higgs particle or even its existence are far from being clarified. Without entering now the details of these deep questions, we feel that, in analogy with the pre-Standard Model situation, a solution to these problems would require a new extraordinary combination of i) experimental discoveries, and ii) theoretical breakthroughs.

The aim of this book is to illustrate, in a pedagogical way, the most precise experimental verifications of the Standard Model to date. These were obtained by the thorough study of the two massive resonances, whose role in the model turns out to be crucial : the Z and the W bosons.

As we shall see, the results of campaigns of experiments at LEP and SLC, as well as at $p\bar{p}$ colliders, have established in a definitive way many features of the Model, and probed it with an unprecedented accuracy. The main results of these investigations will be discussed in detail in this book, with special emphasis on precise measurements of several quantities sensitive to electroweak radiative corrections.

This last point, on one hand, provided beautiful confirmation of the validity of the theoretical scheme. On the other hand, the sensitivity of Electroweak radiative corrections to virtual particles, albeit too massive to be directly accessible to experimental observation, has led to the prediction of the top quark mass, well before this particle was observed directly in $p\bar{p}$ collisions. One must honestly say that a major building block of the Standard Model is still missing, since the Higgs boson has not yet been discovered in direct searches. However, once the top quark mass was experimentally known, the interest of radiative corrections as indirect probes of unknown effects was considerably enhanced, since the only remaining open question, at least in the framework of the Standard Model, would be that of the Symmetry Breaking mechanism. In fact, from a combined analysis of several independent measurements, it has become possible to reach two fundamental conclusions. The first one is that, if the unknown mechanism of symmetry breaking were different from that advocated by the Standard Model, its visible manifestations would be practically indistinguishable at the available level of precision. The second conclusion is that, if the Standard Model is correct, the Higgs boson must be relatively light, i.e. well accessible to the next generation of colliders.

This book begins with a short introduction to weak interactions. The main virtues of Fermi theory are reviewed, together with its main deficiencies that led to the introduction of the intermediate massive vector bosons. The essential features of the Standard Model, in particular the Higgs mechanism, are subsequently quickly summarized. The discussion of specific processes is organized in the book in the following way: in the first part, we discuss the physics of the Z boson, starting with the tree level calculation of electron-positron annihilation into fermion pairs, $e^+e^- \to f\bar{f}$, given in Chapter 2. This contains the expressions of total cross-sections, angular distributions, Z partial decay widths. Particles polarization effects, especially longitudinal polarization, are given.

Since this is one of the main motivations of precision electroweak measurements, it is natural to continue in Chapter 3 with a pedagogical description of the virtual electroweak radiative effects. A one-loop treatment is given here, working in the approximation of massless final fermions, with goal to provide understanding of the structure of these virtual effects, and of why and how they are sensitive to heavy physics, symmetry breaking and possibly new particles. A particular attention is given to the running of α_{QED}, as this constitutes an important source of uncertainty. The specially relevant case of massive final fermions is treated in detail in Chapter 4, with emphasis on $b\bar{b}$ production. The main results of Chapters 3 and 4 are summarized in a table that concludes the description of the one-loop treatment.

After a short description of the main experimental tools for Z and W physics, i.e. high energy colliders and detectors, the detailed discussion of the high-precision tests of the electroweak theory starts in Chapter 6. This Chapter describes what constitutes arguably the most unique achievement of LEP: the measurement of the Z lineshape. A discussion of the global strategy, including the estimate of real radiation of photons, that plays a very important rôle in this particular set of measurements, is followed by a

THE PHYSICS OF THE *Z* AND *W* BOSONS

detailed account of the measurements of cross-sections, including luminosity monitoring and Z decay event selection. The first historical result of LEP and SLC, the determination of the number of light neutrino species, is described and commented. From the lineshape one obtains precise determinations of the Z mass and width, that will probably remain unchallenged for some time, and a complete set of Z leptonic and inclusive hadronic partial widths. In Chapter 7 the main experimental issues involving Z decays to heavy quarks are discussed. The necessary tools related to beauty and charm quark tagging are introduced. These sophisticated methods allow, for instance, the precise determination of the partial Z decay into $b\bar{b}$ and of the b and c quark asymmetries, whose rôle for the high precision tests turns out to be particularly relevant. In Chapter 8 we come to some of the observables that are most sensitive to Electroweak Radiative Corrections involving the Higgs boson, in particular we shall consider the longitudinal polarization asymmetry, measured at the SLC, the τ lepton polarization and the unpolarized forward-backward asymmetries of leptons and quarks. Chapter 8 ends with a summary of all measurements of the leptons and quarks couplings.

In the following Chapter (Chapter 9), the focus moves from the Z boson to the W boson. After a description of W production processes at colliders, a discussion is given of one of the most important parameters measurable at these machines, the W mass. In fact, the production of W bosons opens the possibility of performing direct tests of the sector of the electroweak interactions related to gauge boson-gauge boson couplings. The precision measurements of the triple gauge couplings required by the model are here discussed in some detail.

In the final Chapters of the book, the direct production of the top quark and of the Higgs boson are discussed; results are compared to bounds from electroweak precision tests. After a brief review of top physics, mostly devoted to its discovery and to the measurement of its mass at the Tevatron (Chapter 10), a detailed description of the searches for the Higgs boson at LEP is given in Chapter 11. This is followed by a discussion about the indirect bounds on the Higgs boson mass, and by the results of a model-independent analysis of electroweak data. A short conclusive Chapter 12 discusses the outlook for further improvements in the domain of high precision tests at future colliders.

R. Tenchini
C. Verzegnassi

THE PHYSICS OF THE *Z* AND *W* BOSONS