Preface

Quantum Chromodynamics (QCD) is the theory of the strong interaction, one of the four fundamental forces in nature. It describes the interactions between quarks and gluons, and in particular how they bind together to form the class of particles called hadrons, of which the proton and neutron are familiar examples. QCD emerged as a mathematically consistent theory in the 1970s, and nowadays is regarded as one of the cornerstones of the 'Standard Model' of the elementary particles and their interactions.

Collider physics has grown from a small part of the subject in the 1960s to the position it now holds as the principal method of high-energy physics research. Particle colliders provide the highest available centre-of-mass energies and permit us to probe the structure of matter at the shortest distances. On these scales, all of the known fundamental interactions except gravity can be studied in unprecedented detail. In this book, in order to limit the scope, and not stray too far from our field of expertise, we concentrate mainly on the strong interaction aspects of collider physics, which are described by QCD.

One of the triumphs of modern particle physics has been the extent to which QCD has successfully accounted for the strong interaction processes observed at colliders, most notably the dramatic phenomena of hadronic jet and heavy quark production. Our aim here is to show what has been achieved in this area, while indicating the directions that need further development. Increasingly the study of QCD also has an 'engineering' aspect. In order to exploit the potential of high-energy colliders to study other physics, especially at machines with circulating hadron beams, one needs a quantitative understanding of QCD.

After a general description of the QCD Lagrangian and its symmetries in the first Chapter, we concentrate in Chapter 2 on the crucial properties of asymptotic freedom and colour confinement. Because of the asymptotic freedom of QCD, the appropriate calculational technique at the short

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distances probed by colliders is perturbation theory. The treatment of perturbative QCD is developed in analogy with perturbative Quantum Electrodynamics, with which we assume the reader has some familiarity. In subsequent chapters we describe how short-distance cross sections are calculated, and how the results of these calculations compare with experiment. In Chapters 3 and 4, this is done in detail for the 'classic' QCD processes of high-energy electron-positron annihilation and deep inelastic lepton-hadron scattering. Chapters 5 and 6 then deal with the properties of hadronic jets, while Chapter 7 discusses the production of jets and photons in hadron-hadron collisions.

A large part of collider physics is concerned with the production of massive particles: the gauge and Higgs bosons of the electroweak interaction, and heavy quarks. The relevant properties of electroweak interactions are reviewed in Chapter 8, and then, in Chapters 9 – 11, the production and decays of these particles are discussed, with emphasis on their QCD aspects. Finally in Chapter 12 we summarize the various ways of measuring the one fundamental parameter of QCD: the strong coupling constant α_S.

Much of the theoretical challenge of perturbative QCD derives from extending the well-tried methods of QED to the novel and more complicated context of a non-Abelian gauge theory. There are, however, important differences between the two theories, primarily because the quanta of QCD, quarks and gluons, the analogues of electrons and photons in QED, are confined inside hadrons and not observed as free particles. At long distances, confinement effects predominate, and non-perturbative methods become more appropriate. The most developed of these is lattice QCD, which we review briefly in Chapter 2. Even in the shortest-distance processes, one cannot avoid confinement effects, because the asymptotic incoming and/or outgoing states consist of hadrons. At present, the lattice technique cannot predict such effects in dynamical scattering processes. For certain quantities, however, factorization theorems permit the short- and long-distance dynamics to be separated, and the latter can be treated by parametrizations or model calculations. This has led to the 'industries' of fitting and modelling structure functions (for incoming hadrons) and hadronization or fragmentation distributions (for outgoing ones), which we also review in the appropriate places.

Our intention in writing this book has been to provide an introduction to the physics of high-energy colliders with special emphasis on the study of QCD. We wanted to produce a book which would give an overview of the subject as it stands today while providing a firm basis for understanding future developments. The resulting work is therefore neither a textbook nor a research monograph, but something of each. Above all, we wanted to stress the relationship between theory and experiment.

This book is an outgrowth of lectures which we have given over the

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years in many different places. The level of treatment is suitable for a graduate student who has followed a first course in quantum field theory. At the same time, since we have attempted to give a fuller set of references than is usual in such a book, including references to original work, the book will be a suitable point of departure for researchers who wish to find out about aspects of the subject with which they are not so familiar. For the same reason we have chosen to group the references at the end of each chapter rather than at the end of the book. Although we have tried to ascribe credit correctly, the principal criterion in our choice of references has been to refer to readily accessible published works which we judge will be of use to the reader.

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