This book provides a pedagogical introduction to the perturbative and non-perturbative aspects of quantum chromodynamics (QCD).

Introducing the basic theory and recent advances in QCD, it also reviews the historical development of the subject up to the present day, covering pre-QCD ideas of strong interactions such as the quark and parton models, the notion of colours, current algebra and the S-matrix approach. The author then discusses tools of quantum field theory, the symmetry and quantization of gauge theory, techniques of dimensional regularization and renormalization, QED high-precision tests, deep inelastic scattering and hard processes in hadron collisions, hadron jets, and inclusive processes in e + e− annihilations. Other topics include power corrections and the technologies of the Shifman–Vainshtein–Zakharov (SVZ) operator product expansion, renormalizations and phenomena beyond the SVZ expansion. The final parts of the book are devoted to modern non-perturbative approaches to QCD, such as lattice and effective theories, and the phenomenological aspects of QCD spectral sum rules.

The book will be a valuable reference for graduate students and researchers in high-energy particle and nuclear physics, both theoretical and experimental.

STEPHAN NARISON graduated from the University of Antananarivo, Madagascar and received his Doctorat d'Etat from the University of Marseille. He is currently Director of Research in theoretical physics at the French Centre National de la Recherche Scientifique (CNRS), at the Laboratoire de Physique Mathématique et Théorique de l'Université Montpellier II. He has conducted research in laboratories and university departments throughout the world. Starting his research in the high-precision tests of QED, his main area of research is in non-perturbative aspects of QCD, using QCD spectral sum rules to study the properties of hadrons and low-energy phenomena in terms of the fundamental parameters from QCD first principles. He has worked in this field for more than two decades and has actively participated in its development. Professor Narison has had numerous publications in leading journals, as well as contributing to several books on high-energy physics. He is also the founder and chairman of the QCD Montpellier International Conference Series.

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QCD AS A THEORY OF HADRONS

From Partons to Confinement

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To Larry and Rindra

Contents

About Stephan Narison

He is, at present, a Directeur de Recherche at the French 'Centre National de la Recherche Scientifique' (CNRS) in theoretical physics (section of high-energy elementary particle physics) at the 'Laboratoire de Physique Mathématique et Théorique de l'Université de Montpellier II' (France). He is the founder and chairman of the Series of Montpellier International Conference in Quantum ChromoDynamics (QCD) since 1985 which has been sponsored from 1996 to 2001 by the European Commission of Brussels.

He graduated at the Lycée Gallieni and University of Antananarivo (Madagascar) in 1972. After his master's degree, he was a teacher in different colleges of Antananarivo (Ambatonakanga, Esca and St Michel). In 1974, he obtained a fellowship from the 'Centre International des Etudiants et Stagiaires' of the European Commision of Brussels for preparing his Doctorat d'Etat at the University of Marseille (France). He was offered a 2-year postdoctoral position at the Abdus Salam Center for Theoretical Physics (former International Center for Theoretical Physics) in Trieste (Italy) from 1979 to 1981, a Scientific Associate position for 1 year at LAPP-Annecy (France) and a 2-year CERN (Geneva) fellowship in the Theory division in 1982. He obtained his permanent position in Montpellier in 1984. Since then, he has visited different world high-energy physics laboratories for the purpose of joint collaborations or by simple invitations. These include the traditional West European Universities and Institutes [Universities of Barcelona, Madrid, Valencia (Spain); University of Heidelberg (as a Von-Humboldt fellow), Munich (Germany), Vienna (Austria); CERN-Geneva, University of Bern (Switzerland); ICTP-Trieste, University of Pisa (Italy)], the Universities and Institutes of East European countries [University of Kracow (Poland), INR-Moscow (Russia)], the American Universities and Institutes [LBL (California), SLAC (Stanford), Brookhaven (Upton)] and the more exotic Asian Universities and Institutes [KEK-Tsukuba (Japan), KIAS-Seoul (Korea), NCTS-Hsinchu (Taiwan)]. He also participates actively in the creation of a new Theoretical Physics Institute in his home country. Finally, he is regularly invited to present contributions in the different large-scale, high-energy physics conferences (EPS, IHEP, . . .) and specialized workshops.

His first research activity, which made him known in the field, was the estimate of the hadronic contributions to the anomalous magnetic moment of leptons (subject of his 3ème cycle thesis). Since then, his main research activity has been in the non-perturbative aspects of QCD using the method of QCD spectral sum rules for studying the properties of hadrons

and low-energy phenomena. He has worked in this field since the date of its invention in 1979 and participates actively in its theoretical developments and new applications.

He is a member of the European Physical Society, a correspondant member of the 'Academie Nationale Malgache', a member of the New York Academy of Sciences, nominated in the Who's Who biography by the American Biographical Institute (ABI) (USA) and by the International Biographical Center of Cambridge (IBC) (UK), nominated among the 2000 exceptional men of the twentieth and twenty-first centuries by the ABI and the IBC. He has also been the President-Foundator of the 'Association Culturelle Malgache de Montpellier' (France) since 1993.

Outline of the book

This book provides:

- A pedagogical introduction to the perturbative and non-perturbative aspects of Quantum Chromo Dynamics (QCD), which is expected to be accessible by pre-Ph.D. students who want to learn this field.
- A status of the modern developments in the field.
- An update of the different results presented in the older though successful review [2] and book [3], taking into account the developments of the field within these past 10 years.
- An extension and improvements of the presentation used in these previous review and book, where the QSSR results are compared with those from other non-perturbative approaches.

The book is divided into ten parts:

- In the first part, one starts from a general introduction to particle physics and historical survey on the developments of strong interactions prior to QCD. Then, we discuss the main ideas and basic tools of the field.
- In the second part, we present the gauge theory aspect of QCD.
- In the third part, we discuss in details the most popular techniques of dimensional regularization and renormalization and discuss some of its applications both in QCD and QED.
- In the fourth part, we present different QCD hard deep inelastic processes at hadron colliders, and discuss different unpolarized and polarized structure functions.
- In the fifth part, we present the QCD hard processes in e^+e^- processes and discuss jets, fragmentation functions and totally inclusive processes.
- In the sixth part we summarize QCD tests and α_s measurements.
- In the seventh part, we discuss power corrections and mainly the theoretical basis and technologies of the Shifman–Vainshtein–Zakharov operating product expansion (OPE).
- In the eighth part, we present a compilation of different QCD two-point functions obtained from perturbative calculations and the SVZ-expansion. These expressions are basic ingredients for various phenomenological applications.
- In the ninth part, we present different aspects of modern non-perturbative approaches to QCD.
- In the tenth part, we present extensive phenomenological aspects of QCD spectral sum rules.
- The Appendices collect different useful conventions and formulae for QCD practitioners.
- The Contents, References and Index are useful for a quick guide for readers of the book.

Preface

Quantum Chromodynamics (QCD) continues to be an active field of research, which one can see from the number of publications in the field, as well as from the number of presentations at different QCD dedicated conferences, such as the regular QCD-Montpellier Conference Series. This continuous activity is due to the relative difficulty in tackling its non-perturbative aspects, although its asymptotic freedom property has facilated perturbative calculations of different hard and jet processes. Therefore, we think it is still useful to write a book on QCD in which, besides the usual pedagogical introduction to the field, some reviews of its modern developments, which have not yet been 'compiled' into a book, will be presented. Elementary introductions at the level of pre-Ph.D. in different specialized topics of QCD will be discussed, which may be useful for a future deeper research and for a guide in a given subject.

We start the book with a general elementary introduction to strong interactions, parton and quark models, . . . , and present the basic tools for understanding QCD as a gauge field theory (renormalization, operator product expansion, . . .). After, we present the usual hard processes (deep inelastic scattering, jets, . . .) calculable in perturbative QCD, and discuss the resummation (renormalons, . . .) of the perturbative series. Later, we discuss the different modern non-perturbative aspects of QCD (lattice, effective theories, . . .). Among these different methods, we discuss extensively, the method and the phenomenology of the QCD spectral sum rules (QSSR) method introduced in 1979 by Shifman–Vainshtein and Zakharov (hereafter referred to as SVZ) [1]. Indeed, we have been impressed by its ability to explain low-energy phenomena such as the hadron masses, couplings and decays in terms of the first few fundamental parameters of QCD (QCD coupling, quark masses, quark and gluon condensates), and vice versa, we have been fascinated by the success of the method to extract the QCD universal parameters from experiments. In this respect, some parts of this book have been updated, improved, extended and included a latex version of the former review [2]:

Techniques of dimensional regularization and renormalization for the two-point functions of QCD and QED, S.N., *Phys. Rep*. 84 (1982) 263

and of the book [3]:

QCD Spectral Sum Rules Lecture notes in Physics, Vol. 26 (1989) World Scientific Publ. Co. Singapore.

However, the discussions in this book cannot replace the previous ones (hereafter referred to as QSSR1), as some detailed analyses carried out in the older review and book are not reported and repeated here. In this present book, we limit ourselves to review the most recent results and new developments in the field, without going into some technical details, and, in this sense, this book is a useful supplement to the former. Various misprints in QSSR1 have also been corrected.

As we have already mentioned, and as in the previous review and book, we have written this book for a large audience, not necessarily working in the field (elementary introduction to QCD, . . .). However, experts will also appreciate this book, as they will find the most relevant and the latest results obtained so far with the QSSR method. They can also find compilations of non-trivial QCD expressions of the two-point correlators obtained within the Operator Product Expansion (OPE), and technical points relevant to the method itself (mixing of operators under renormalizations, validity of the SVZ expansion . . .). Experimentalists will find in this book a 'quick review' of most of important results obtained from QSSR.

However, because of the large *horizontal* spectrum of the QSSR applications in different branches of low-energy physics, including nuclear matters, which we (unfortunately) cannot cover in this book, we shall limit ourselves to the well-controlled and simplest applications of the methods, namely the light and heavy quark systems and to a lesser extent the gluonia and hybrid meson channels. At present, these examples are quite well understood and will, therefore, serve as *prototype* applications of QSSR in high-energy physics and quantum field theory. Some other applications of QSSR, such as in the QCD string tension, in the composite models of electroweak interactions (QHD sum rules) and in supersymmetric QCD, were already discussed in QSSR1 and will not be discussed in detail here, since there has been no noticeable recent developments in these fields of applications, since the publication of QSSR1. We shall not discuss the uses of QSSR for nuclear matters, either, since the complexity of these phenomena still needs to be better understood. However, the enthusiasm of nuclear physicists for using this method in the baryonic sector might be restrained, owing to the delicateness of the corresponding analysis, which in my opinion has not yet been improved since the original work, in which the obstacle is due to the optimal choice of the nucleon operators. At the present stage, one can only consider the analysis done in the baryon sector to be very qualitative.

Following (actively) the developments of QCD through those of QSSR since its birth in 1979, my feeling à la Feynman (Omni magazine 1979), advocated in QSSR1 about this field remains unchanged (as already quoted in QSSR1):

. . . A few years ago, I was very skeptical . . . I was expecting mist and now it looks like ridges and valleys after all . . . ,

while the *great* success of QSSR in the understanding of the complexity of low-energy non-perturbative phenomena and hadron physics, is well illustrated by the Malagasy saying:

'Vary iray no nafafy ka vary zato no miakatra!.'

which means: with one grain of rice sowed, one can gather by the thousand!, or in other words, the method has started quite modestly and, with time, it has become more and more underground. Indeed, at present, QSSR (*used correctly*) is one of the most powerful methods for understanding (*analytically*) the low-energy dynamics of hadrons using the few fundamental parameters (coupling, masses and condensates) coming from QCD first principles.

Acknowledgements

This book is a result of my attendance (as a chairman) at the QCD–Montpellier International Conference series from which I have learned a lot about the developments of QCD. It also comes from long-term contributions on QCD spectral sum rules and I thank former collaborators and colleagues who have contributed to the developments of this important field. Most of the figures of this book comes from the efficient work of Arlette Coudert from Cern. This work has been completed when I visited different institutes during the last 5 years (Cern–Geneva, Kek-Tsukuba, Ncts HsinChu, Ntu Taipei, Antananarivo University, MPI-Munich, Heidelberg University) and I wish to thank them for their hospitality. Finally, I am grateful for the patience of my family and friends who have sacrificed life-years during the long write-up of these materials, and I wish to thank them for their generous support.