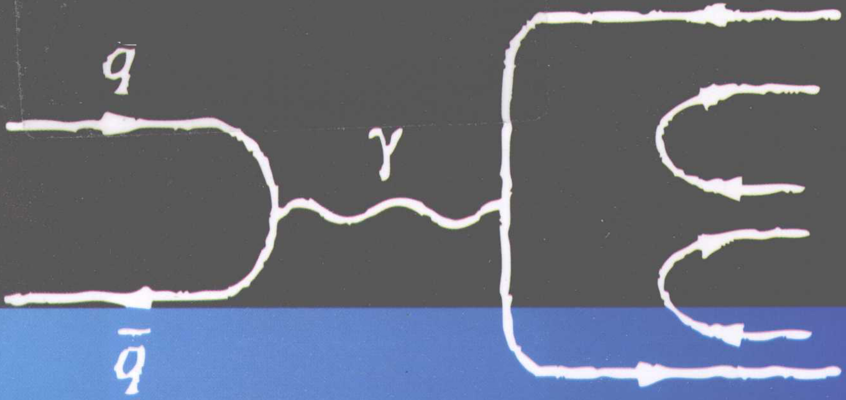
Elliot Leader， Enrico Predazzi

An Introduction to Gauge Theories and Modern Particle Physics

Vol.1



规范理论和现代粒子物理学导论 第1卷

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AN INTRODUCTION TO GAUGE THEORIES AND MODERN PARTICLE PHYSICS, VOLUME 1

Electroweak interactions, the 'new particles' and the parton model

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Preface

For a book of its genre, our previous book, *An introduction to gauge theories and the "new physics"* (1982) was a great success. It was not, alas, sold in airport lounges, but it did run to two additional printings (1983, 1985), and to extensively revised editions in Russian (1990), and in Polish (1991). More importantly, it seemed to achieve the principal goal which we had set ourselves, namely, to present a *pedagogical* account of modern particle physics with a balance of theory and experiment, which would be intelligible and stimulating for both theoretical and experimental graduate students. We did *not* try to write a profound book on field theory, *nor* a treatise on sophisticated experimental techniques. But we did wish to stress the deep, intimate and fruitful interaction between theoretical ideas and experimental results. Indeed, for us, it is just this aspect of physics which makes it seem so much more exciting than say pure mathematics. Our greatest pleasure came from the favourable reaction of students who were working through the book and from those reviewers who caught what we hoped was its essential flavour—'the writing creates the feeling of an active progression of ideas arising from the repeated interaction of theoretical prejudice with experimental observation', 'unlike most textbooks, it is highly readable, and makes everything appear simple and obvious'. Well, the last comment is surely an exaggeration but that was our aim.

In thinking about a second edition we were faced with a serious conceptual problem. Ten years ago we were in a state of excited expectation. A beautiful theory had been created and led, via the simplest of calculations, to absolutely dramatic experimental predictions; principally the existence and basic properties of the heavy vector bosons $W^\pm$ and Z^0. A host of interesting new phenomena could be studied with no more effort than the calculation of a lowest order Born diagram. Much of the new physics could be discussed and understood from rather qualitative arguments. That idyllic situation is much changed now.

After the few years during which the experimentalists were struggling to demonstrate the very existence of these new phenomena, when the world of physics was electrified by the discovery of *one single* W or Z event, we have moved into an era when LEP is mass-producing millions of Z^0s!

Consequently, and unavoidably, the physics emphasis has changed drastically. Now it is the fine quantitative detail, the precise width and line shape of the Z^0, precision measurements of forward-backward asymmetries and branching ratios etc. which are under scrutiny experimentally. And to match that, more sophisticated and vastly more complicated theoretical calculations are demanded. Thus we have passed from a simple heuristic era to one of demanding quantitative rigour.

One consequence is that instead of a second edition we have ended up with a large new two-volume book!

The above does not mean that the subject has become boring and moribund. On the contrary, great theoretical issues are at stake. For the earlier Born approximations did not really test the deeper *field-theoretic* aspects of the theory, whereas the present comparisons between theory and experiment *are* sensitive to these elements. They play a rôle almost like that of the Lamb shift in establishing the validity of quantum electrodynamics (QED).

Faced then with the need to introduce and discuss these more extensive calculations, and given that schoolchildren, so it seems, are taught about quarks and gluons, there was the temptation to abandon the long and leisurely historical introduction to partons, quarks and gluons that we had provided in the first edition.

We have not done so for the following reason. The introduction of the new level of 'elementarity', the quarks and gluons, beyond the level of mesons and baryons, is, we believe, of a fundamentally new kind, both physically and philosophically in the modern history of science. For in all previous cases the *ultimate* proof of the existence of a hypothesized constituent was to produce and identify that constituent in the laboratory, for example, via a track in a bubble-chamber; or, where a neutral particle was involved, like the Λ^0, to have very obvious and incontrovertible evidence of its propagation and decay into charged tracks.

Now, for the first time, we are postulating the existence of constituents which, according to the present interpretation of the theory, can never be truly freed, which can, *in principle*, never be seen as free particles in the laboratory. This means that we really must provide convincing evidence for these constituents and must examine very critically the steps that lead to our postulating their existence.

It is on these grounds we have decided to retain the detailed discussion of the historical process leading to the belief in the parton picture.

The major *new* features of this book are:

1. We give a detailed explanation of higher order electroweak effects (the so-called radiative corrections).
2. We provide a much expanded discussion of quark mixing (the Kobayashi–Maskawa matrix), of K^0–$\bar{K}^0$ and B^0–$\bar{B}^0$ mixing and new sections on both the phenomenology and dynamics of CP violation.
3. The sections on charm and beauty and on jet physics have been totally revised in order to take into account the mass of data that has accumulated over the past few years.
4. We have enlarged the treatment of deep inelastic lepton–hadron scattering in three directions. Catalyzed by the major discoveries of the European Muon Collaboration there is a more detailed treatment of both polarization effects and of nuclear effects. And in anticipation of HERA we discuss Z^0–γ interference which will be important for large Q^2 physics.
5. The treatment of QCD corrections to the simple parton model is presented in much more detail and a new chapter is devoted to the derivation of the parton model from field theory.
6. Also linked to the coming into operation of HERA we discuss in more detail the 'low x' region in deep inelastic scattering. Here the usual evolution equations break down and one approaches the non-perturbative region of QCD, creating a tremendous challenge to theory.
7. A brief discussion of elastic and soft reactions is provided so as to give the reader at least an inkling of the remarkable $\bar{p}p$ physics being carried out at the CERN collider and at the Fermilab Tevatron. In particular, we discuss the impact of the very unexpected result of the UA4 experiment at CERN.
8. An introduction is given to the many and varied attempts to deal with the non-perturbative or confinement region of QCD, especially to the lattice approach and to the sum rule method, and to the exciting new ideas about baryon and lepton number violations. Necessarily the treatment of these is rather brief and not very comprehensive. We seek to convey the basic ideas and methods.
9. The Appendix has been much enlarged. It now contains a more detailed specification of the Feynman rules for electroweak theory and QCD, and a discussion of the relations between S-matrix, transition

amplitudes and Feynman amplitudes. There are also sections on CPT invariance and on the operator form of Feynman amplitudes or effective Hamiltonians, both important for CP violation. The evaluation of matrix elements of conserved currents, much used in deep inelastic scattering and in the study of the Kobayashi-Maskawa matrix, is explained in some detail. Finally, a complete list of cross-section formulae for all 2 → 2 partonic reactions is given.

It is fascinating to step back and to view what has been achieved in the past decade and where we now stand. Electroweak theory and quantum chromodynamics have been remarkably successful, even at the level of the detailed questions now being examined. But essential to their present formulation and to their success are two objects, two crucial ingredients, the top quark and the Higgs meson, which have not yet been found. The Higgs meson is central to the symmetry breaking mechanism which gives mass to the W and Z bosons. And the top quark plays a vital rôle in the cancellation of anomalies and in the higher order calculations of small but significant effects beyond the Born approximation. Indeed the success in comparing these small corrections with experiment has led to quite tight limits on what mass the top quark could have. Most recently, at the Dallas Conference on High Energy Physics in August 1992, the following remarkably narrow limits for m_t were reported:

$$\begin{array}{lll}
107 \le m_t \le 143\ \mathrm{GeV}/c^2 & \text{for} & m_H = 60\ \mathrm{GeV}/c^2, \\
126 \le m_t \le 162\ \mathrm{GeV}/c^2 & \text{for} & m_H = 300\ \mathrm{GeV}/c^2, \\
143 \le m_t \le 179\ \mathrm{GeV}/c^2 & \text{for} & m_H = 1\ \mathrm{TeV}/c^2.
\end{array}$$

In a way the sense of expectation for the discovery of 'top' and the 'Higgs' is almost as strong as was the expectation of the W and Z a decade ago.

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Finally, there are many colleagues and friends, too many to mention individually, to whom we are indebted for providing data and comments and for drawing our attention to misprints and errors in the first edition.

Notational conventions

Units

Natural units $\hbar = c = 1$ are used throughout.

For the basic unit of charge we use the *magnitude* of the charge of the electron: $e > 0$.

Relativistic conventions

Our notation generally follows that of Bjorken and Drell (1964), in *Relativistic Quantum Mechanics.*

The metric tensor is

$$g_{\mu\nu} = g^{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}.$$

Space-time points are denoted by the contravariant four-vector x^μ ($\mu = 0, 1, 2, 3$)

$$x^\mu = (t, \boldsymbol{x}) = (t, x, y, z),$$

and the four-momentum vector for a particle of mass m is

$$p^\mu = (E, \boldsymbol{p}) = (E, p_x, p_y, p_z),$$

where

$$E = \sqrt{\boldsymbol{p}^2 + m^2}.$$

Using the equation for the metric tensor, the scalar product of two four-vectors, A, B, is defined as

$$A \cdot B = A_\mu B^\mu = g_{\mu\nu} A^\mu B^\nu = A^0 B^0 - \boldsymbol{A} \cdot \boldsymbol{B}.$$

γ-matrices

The γ matrices for spin-half particles satisfy

$$\gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2g^{\mu\nu}$$

and we use a representation in which

$$\gamma^0 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}, \quad \gamma^j = \begin{pmatrix} 0 & \sigma_j \\ -\sigma_j & 0 \end{pmatrix}, \quad j = 1,2,3,$$

where σ_j are the usual Pauli matrices. We define

$$\gamma^5 = \gamma_5 = \mathrm{i}\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}.$$

In this representation one has for the transpose T of the γ matrices:

$$\gamma^{j\mathrm{T}} = \gamma^j \qquad \text{for} \quad j = 0,2,5,$$

but

$$\gamma^{j\mathrm{T}} = -\gamma^j \qquad \text{for} \quad j = 1,3.$$

For the Hermitian conjugates † one has

$$\gamma^{0\dagger} = \gamma^0, \qquad \gamma^{5\dagger} = \gamma^5,$$

but

$$\gamma^{j\dagger} = -\gamma^j \qquad \text{for} \quad j = 1,2,3.$$

The combination

$$\sigma^{\mu\nu} \equiv \frac{\mathrm{i}}{2}[\gamma^\mu, \gamma^\nu]$$

is often used.

The scalar product of the γ matrices and any four-vector A is defined as

$$\not{A} \equiv \gamma^\mu A_\mu = \gamma^0 A^0 - \gamma^1 A^1 - \gamma^2 A^2 - \gamma^3 A^3.$$

For further details and properties of the γ matrices see Appendix A of Bjorken and Drell (1964).

Spinors and normalization

The particle spinors u and the antiparticle spinors v, which satisfy the Dirac equations

$$\begin{aligned} (\not{p} - m)u(p) &= 0, \\ (\not{p} + m)v(p) &= 0, \end{aligned}$$

respectively, are related by

$$\begin{aligned} v &= \mathrm{i}\gamma^2 u^*, \\ \bar{v} &= -\mathrm{i}u^{\mathrm{T}}\gamma^0\gamma^2, \end{aligned}$$

where $\bar{v} \equiv v^\dagger\gamma^0$ (similarly $\bar{u} \equiv u^\dagger\gamma^0$).

Note that our spinor normalization differs from Bjorken and Drell. We utilize

$$u^\dagger u = 2E, \qquad v^\dagger v = 2E,$$

the point being that the above can be used equally well for massive fermions and for neutrinos. For a massive fermion or antifermion the above implies

$$\bar{u}u = 2m, \qquad \bar{v}v = -2m.$$

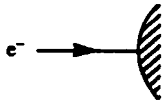
Cross-sections

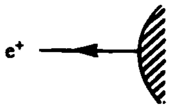
With this normalization the cross-section formula (B.1) of Appendix B in Bjorken and Drell (1964) holds for both mesons and fermions, massive or massless. This is discussed in our Appendix 2—see in particular eqn (A2.1.6).

Fields

Often a field like $\psi_\mu(x)$ for the muon is simply written $\mu(x)$ or just μ if there is no danger of confusion.

In fermion lines in Feynman diagrams the arrow indicates the direction of flow of *fermion number*. Thus incoming electrons or positrons are denoted as follows:





Normal ordering

In quantum field theory the products of operators that appear in Lagrangians and Hamiltonians should really be *normal ordered* with all creation operators to the left of all annihilation operators. With the exception of Sections 5.1.1 and 19.4 this is irrelevant throughout this book, so the normal ordering symbol is never indicated.

Group symbols and matrices

In dealing with the electroweak interactions and QCD the following symbols often occur:

- n_f = number of flavours;
- N which specifies the gauge group $SU(N)$—Note that $N = 3$ for the colour gauge group QCD;
- the Pauli matrices are written either as $\boldsymbol{\sigma}_j$ or $\boldsymbol{\tau}_j$ ($j = 1, 2, 3$);
- the Gell-Mann $SU(3)$ matrices are denoted by $\boldsymbol{\lambda}^a$ ($a = 1 \ldots 8$);
- for a group (G) with structure constants f_{abc} one defines $C_2(G)$ via

  $$\delta_{ab} C_2(G) \equiv f_{acd} f_{bcd}$$

  and one often writes

  $$C_A \equiv C_2[SU(3)] = 3.$$

If there are n_f multiplets of particles, each multiplet transforming according to some representation R under the gauge group, wherein the group generators are represented by matrices $\boldsymbol{t}^a$, then $T(R)$ is defined by

$$\delta_{ab} T(R) \equiv n_f Tr(\boldsymbol{t}^a \boldsymbol{t}^b).$$

For $SU(3)$ and the triplet (quark) representation one has $\boldsymbol{t}^a = \boldsymbol{\lambda}^a/2$ and

$$T \equiv T[SU(3); \text{triplet}] = \tfrac{1}{2} n_f.$$

For the above representation R one defines $C_2(R)$ analogously to $C_2(G)$ via

$$\delta_{ij} C_2(R) \equiv t^a_{ik} t^a_{kj}.$$

For $SU(3)$ and the triplet representation one has

$$C_F \equiv C_2[SU(3); \text{triplet}] = 4/3.$$

The coupling in QCD

Finally, to conform with recent review articles, we have changed the sign convention for the coupling in QCD, i.e. our new g is minus the g used in the first edition. Since everything of physical interest in QCD depends upon g^2 this is essentially irrelevant.

Colour sums in weak and electromagnetic current

Since the weak and electromagnetic interactions are 'colour-blind' the colour label on a quark field is almost never shown explicitly when dealing with electroweak interactions. In currents involving quark field operators (e.g. in Sections 1.2 and 9.3) a *colour sum is always implied.* For example, the electromagnetic current of a quark of flavour f and charge Q_f (in units of e) is written

$$J^\mu_{\text{em}}(x) = Q_f \bar{q}_f(x) \gamma^\mu q_f(x)$$

but if the colour of the quark is labelled j ($j = 1, 2, 3$) then what is implied is

$$J^{\mu}_{\text{em}}(x) = Q_f \sum_{\substack{\text{colours}\\ j}} \bar{q}_{f_j}(x)\gamma^{\mu}q_{f_j}(x).$$

Perché si scrive?

> ...Per insegnare qualcosa a qualcuno. Farlo, e farlo bene, può essere prezioso per il lettore, ma ... l'intento didattico corrode la tela narrativa dal di sotto, la degrada e la inquina: il lettore che cerca il racconto deve trovare il racconto, e non una lezione che non desidera. Ma appunto, le eccezioni ci sono, e chi ha sangue di poeta sa trovare ed esprimere poesia anche parlando di stelle, di atomi, dell'allevamento del bestiame e dell'apicultura...

Why does one write?

> ...To teach something to someone. To do this and do it well can be valuable for the reader but ... the didactic intention corrodes the narrative canvas from underneath, degrades it and contaminates it: the reader who looks for a story must find a story and not a lesson he does not want. But, of course, exceptions there are, and whoever has the blood of a poet will find and express poetry also when talking of stars, of atoms, of cattle breeding and of the raising of bees...

Primo Levi

Note added in proof: the discovery of the top quark (?)

On Tuesday 26 and Wednesday 27 April 1994 nearly simultaneous press conferences in the USA, Italy and Japan announced that evidence for the top quark had been found by the CDF collaboration at Fermilab. In fact most of the information had by then already appeared in a long article in *The New York Times* and rumours about the discovery had been circulating for some time.

The collaboration was at pains to insist that they were not claming the *discovery* of top, but only some *evidence* for it. There are several reasons for their prudence. The main one is that the $t\bar{t}$ cross-section measured, $13.9^{+6.1}_{-4.8}$ pb, is a factor of three larger than the theoretical expectations. Also the other collaboration at Fermilab studying this question (the DO collaboration) is not yet willing to make any public statement, but it seems that their $t\bar{t}$ cross-section would be considerably smaller. The calculated $t\bar{t}$ cross-section at Fermilab energies is a sensitive function of m_t, varying from 20 pb for $m_t = 120\ \text{GeV}/c^2$ to 4 pb for $m_t = 180\ \text{GeV}/c^2$.

Interestingly, the theoretical estimates of m_t, based on the calculation of radiative corrections to various high precision LEP electroweak measurements, have been moving towards higher and higher values. At the 1990 International High Energy Physics Conference at Singapore the best value was given as $m_t = 137 \pm 40\ \text{GeV}/c^2$, whereas recent studies suggest $164 \pm 16 \pm 19\ \text{GeV}/c^2$. The value for m_t given by CDF is compatible with these higher values, namely $m_t = 174 \pm 13^{+13}_{-12}\ \text{GeV}/c^2$. Such a high value for m_t has significant implications for the radiative correction calculations and in particular for the theoretical understanding of CP violation, as discussed in Chapter 19.

The result reported by CDF is a 2.5 sigma effect, which becomes less then a 2 sigma effect when their data is combined with the DO data, Clearly, therefore, much better data are needed before a totally convincing picture can emerge. The evidence for top, if confirmed, would be one more very strong factor in favour of the standard model. Ultimately, however, there will still remain the crucial question as to the existence or not of the Higgs boson. And it may be some time before we have a definitive answer to *that* question.

By May 1995 the evidence for the top quark is firmer. The new combined CDF and DO results have increased the significance of the signal to more than 4 sigma. The masses quoted are:

$$\begin{aligned} \text{CDF:}\ & 176 \pm 8 \pm 10\ \text{GeV}/c^2 \\ \text{DO:}\ & 199^{+19}_{-21} \pm 22\ \text{GeV}/c^2. \end{aligned}$$

Note added in proof: the demise of the SSC

At various points in this book we have talked rather optimistically about future accelerators, in particular about the gigantic, 54 miles in circumference, Superconducting Super Collider (SSC) which was to be built at Waxahachie in Texas and which would have produced 20 TeV + 20 TeV proton–proton collisions. The energy densities attainable would have matched those found in the universe as close as 10^{-13} seconds to the big bang, providing extraordinary possibilities for testing not just the standard model of elementary particle interactions, but the whole picture of the evolution of the universe.

Alas, on 22 October 1993, after a long and agonizing period of indecision, the US House of Representatives voted to end the funding of the SSC project. At this pont, 2 billion US dollars had already been spent and about one-fifth of the tunnel completed.

In the words of Hazel O'Leary, the US Secretary of State for Energy, 'this decision by Congress ... is a devastating blow to basic research and to the technological and economic benefits that always flow from that research.'

There is still hope that the somewhat more modest European project for a Large Hadron Collider (LHC) with 8 TeV + 8 TeV proton–proton collision, will go ahead. A final decision was due during 1994. After much procrastination the CERN Council finally voted in favour of the project in December 1994. The construction will proceed in stages, with full-scale operation planned for 2008!

Contents: Volume 1

Electroweak interactions, the 'new particles' and the parton model