# Part one

## Introduction

# 1

# The Rise of the Standard Model: 1964–1979

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In the late 1970s elementary particle physicists began speaking of the "Standard Model" as *the* basic theory of matter. This theory is based on sets of fundamental spin-$\frac{1}{2}$ particles called "quarks" and "leptons," which interact by exchanging generalized quanta, particles of spin 1. The model is referred to as "standard," because it provides a theory of fundamental constituents – an ontological basis for describing the structure and behavior of all forms of matter (gravitation excepted), including atoms, nuclei, strange particles, and so on. In situations where appropriate mathematical techniques are available, it can be used to make quantitative predictions that are completely in accord with experiment. There are no well-established results in particle physics that clearly disagree with this theory.

This pleasing state of affairs is quite new in particle physics. It contrasts markedly with the theoretical situation in the early 1960s, when there were a variety of different ideas about the subatomic realm. For example, in 1964 most particle physicists considered protons, neutrons, pions, kaons, and a host of other strongly interacting particles (i.e., hadrons) to be in a certain sense "elementary." By 1979 the consensus had emerged that the hadrons were not elementary after all but are composed of more basic building blocks called quarks, held together by the exchange of another kind of particle called the gluon. Or consider the particle interactions. In 1964 almost all physicists thought the strong, weak, and electromagnetic interactions were independent phenomena, perhaps requiring different types of theories for their description. But fifteen years later, all three interactions had been successfully described by quantum field theories, and the last two were considered to be different aspects of a single unified "electroweak" interaction. Whereas particle physicists of 1964 used many different tongues, those of 1979 spoke a common language.

In this same period, roughly between 1964 and 1979, the entire field of particle physics passed through a profound metamorphosis. All aspects of the discipline – including detection equipment, particle accelerators, and methods of experimental and theoretical analysis – underwent irreversible change. In a wider context, the role and status of particle physics in society, its political support and financial backing, and its demographic basis were also very much altered. It was a period of turbulence, marked by deep intellectual ferment, conflicts, confusion, and some misleading results. Balanced by many remarkable discoveries – most of them discussed in this book – the period of the rise of the Standard Model was an exciting and critical period in the evolution of physics.

The conference on which this book is based, – the Third International Symposium on the History of Particle Physics [held at the Stanford Linear Accelerator Center (SLAC), 24–27 June 1992), was convened to examine this period of particle physics, which we consider to be the third major period in particle physics.[1] Two earlier symposia in this series (held in 1980 and 1985 at Fermi National Accelerator Laboratory, or Fermilab) dealt with the birth of particle physics during the 1930s and 1940s and with the field's adolescence, the period of particle discoveries in the 1950s and early 1960s, which left physics with a veritable "particle explosion."[2]

Starting in 1964, physicists made a serious effort to reduce the number of elementary constituents to a set of three particles with strong interaction – the $u$, $d$, and $s$ quarks – and two leptonic pairs consisting of the electron $e$, and its neutrino $\nu_e$, plus the muon $\mu$, and its neutrino $\nu_\mu$, together with the antiparticles of both quarks and leptons.[3] An alternative school of thought, the "bootstrap" approach, considered all hadrons to be equally elementary (partaking in "nuclear democracy").[4] However, by 1970 evidence from deep-inelastic electron-nucleon scattering experiments at SLAC began to mount in favor of the quark theory, while the 1974 discovery of the $J/\psi$ particle at Brookhaven National Laboratory (BNL) and at SLAC added a fourth quark to the list (the $c$ or "charm" quark). The quark model now proved convincing to many who had been skeptical of it.

In retrospect, the most influential work with regard to a theory of particle interactions was a 1954 paper by Chen Ning Yang and Robert Mills, which introduced the idea of non-Abelian gauge fields.[5] This work caught the imagination of some theorists, but more phenomenologically oriented physicists generally ignored it for years. However, in the 1960s gauge theory gradually brought about a revival of interest in quantum field theories, which, despite the successful renormalization of quantum electrodynamics (QED) in the late 1940s, had failed to provide a satisfactory theory of the nuclear interactions.

Before proceeding to a more detailed discussion of the period of the rise of the Standard Model, we will in the next section set the stage by characterizing with broad strokes all three periods covered by this series of history of physics conferences.

## Three periods of elementary particle physics

### *The birth of particle physics*

Modern particle physics began in the 1930s as an outgrowth of experimental studies of nuclear and cosmic-ray physics being carried out with much improved techniques: electronic counter-arrays, particle-triggered Wilson cloud chambers operated in strong magnetic fields, and new types of particle accelerators. These new instruments made it possible to study interactions between particles up to about 100 MeV (in the target rest frame) and thus to explore behavior at distances of the order of the nuclear radius ($\approx 10^{-15}$ m).

Efforts to understand the new higher-energy regime in terms of concepts extrapolated from below met with only partial success. There followed the usual attempts to develop ad hoc phenomenological models, as well as attempts to apply quantum fields, even though the most useful and best established prototype, QED, was known to have serious problems connected with its high-energy behavior – the problem of the so-called divergences. During the 1930s, the other main quantum field theories developed were Enrico Fermi's theory of $\beta$ decay and Hideki Yukawa's meson theory. Although we now think of these theories as describing, respectively, the weak and strong nuclear forces, in the 1930s they existed as unified theories of both types of nuclear force.[6]

The 1930s actually *began* with a maximally unified picture: All matter, including nuclear matter, consisted of "positive and negative electricity" – protons and electrons, interacting electromagnetically through the exchange of photons. There was thus (to speak anachronistically) a trinity consisting of the first hadron, the first lepton, and the first gauge boson. Soon, however, another trio of particles was found necessary to complete the standard model of its day: the positron, neutron, and neutrino.[7] The last particle, whose existence was conjectured by Wolfgang Pauli, was not observed until 1956.

By 1937 physicists had established that there are new unstable charged particles of mass intermediate between those of the proton and the electron. Named *mesotrons* (as well as other names), these particles were soon conjectured to be the same as the *U particles* that had been the basis for the theory of nuclear forces proposed by Yukawa in 1935. Interrupted by World War II, the remainder of the first period of particle physics was largely concerned with establishing the mass, spin, mean lifetime, and interaction cross section of the mesotrons, and with trying to reconcile them with Yukawa's theory, while the latter was being adapted to the constraints placed upon it by the increasing knowledge of nuclear forces.

A decade after the mesotron discovery, the true Yukawa mesons, now called *pions*, were discovered. Charged pions were identified in 1947 by the University of Bristol group through the tracks pions left in photographic emulsions exposed to high-altitude cosmic rays; the neutral pion was isolated in 1950. The mesotron, renamed *muon*, was found to be a heavy version of the electron (and is now called a second-generation lepton). The renormalization of QED led to great successes in the understanding of electromagnetic interactions, and together with the conjectured "$\mu$–$e$ universality" of the weak interactions, physicists hoped that a consistent and closed (though not unified) "theory of everything" could well be within reach.

However, as is usually the case when the imagined "end of physics" is in sight, there were still a few clouds in the sky. One of these was

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the muon itself, which had no evident role in the structure of matter (e.g., I. I. Rabi's famous comment on the muon, "Who ordered that?"). And if the muon appeared to be an extra piece left over after the theory had been completed, what was one to make of the strange particles, the mysterious cloud-chamber V-tracks discovered in Manchester in 1947, whose variety began to increase at a disturbingly prolific rate?

During the first period of particle physics, research was carried out either by individuals or by groups of a few researchers, sometimes with the assistance of semiprofessional workers, usually women (who were inevitably underpaid and called "girls"). In spite of the terrible social, political, and material conditions prevailing in much of the world during this period, science itself remained rather international in scope and spirit. And for the most part the scientific community remained friendly and cooperative, so far as the war and its aftermath allowed.[8]

## *From pions to quarks*

To explore the new world of the pions and the strange particles, it was not sufficient to rely on chance observations in cosmic rays, which had uncertain composition, diverse energy and momentum, and too low an intensity for systematic experimentation. Therefore, although almost all the new particle discoveries up to 1955 were made using cosmic rays as a source, from that year on particle accelerators took over the job. During the transition, as cosmic-ray physicists struggled to increase their statistics in order to compete with the new accelerators, they found it necessary to work in large groups. (In 1955 the G-stack nuclear emulsion collaboration involved 22 laboratories.) At the accelerator sites also, large groups became the rule, marking a significant change in the culture of high-energy physics.

Although they were used for a variety of studies (for example, to compare the properties of muons and electrons), accelerators of energy up to about 1 GeV were built mainly to study the strong nuclear force. It was argued that their relatively large cost to society was justified, indeed required, by the great practical relevance of nuclear weaponry and nuclear power. This argument carried special force during the period of the Cold War. The research field itself was referred to as *high-energy nuclear physics*, and the adjective *nuclear* was officially dropped only in 1958.[9]

The first sighting of the neutral pion came at the 184 inch, 380 MeV Berkeley cyclotron and was confirmed later that year in cosmic ray ex-

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periments. The first pion–nucleon resonance (the spin $J = \frac{3}{2}$ and isospin $I = \frac{3}{2}$ resonance, or so-called 3-3 resonance, now called N*) was found at the 450 MeV Chicago cyclotron. The interaction properties of pions were extensively explored at cyclotrons capable of producing them (energy $E > 300$ MeV), as well as with the electron synchrotrons that operated in a similar energy range. One important result of the comparison of positive and negative pion-scattering amplitudes from nucleons was the establishment of the charge independence of the strong nuclear force.

Electron-scattering experiments, carried out at Stanford and Cornell, revealed the true size and shape of the nucleons, verifying that they are extended objects with radii $\approx 10^{-15}$ m. They were, of course, already known to have anomalous (that is, non-Dirac) magnetic moments and were assumed to differ from leptons also in other ways, for example by the presence of an extended meson "cloud." This was a good indication that hadrons would have to be treated as complex systems, reinforcing the view of many theorists who rejected the idea that strong interactions could be described in terms of quantum fields.

The real particle explosion began with the accelerators that operated in the multi-GeV range: the Cosmotron at BNL and the Bevatron at the Berkeley Radiation Laboratory (now the Lawrence Berkeley Laboratory, or LBL). At the same time, more sensitive visual detectors, the high-pressure diffusion cloud chamber and the bubble chamber, whose medium could serve also as a target, permitted the convenient viewing of the resulting long high-energy tracks. Now detailed studies could be made of the production and decay of the strange particles. These studies verified the idea of *associated production* (i.e., strong production in pairs, but weak decay) to explain the puzzling behavior that had earned them the name "strange." The behavior was then attributed in 1955 by Kazuhiko Nishijima and Murray Gell-Mann (independently) to an additive quantum number, called "strangeness" by Gell-Mann. This strangeness quantum number, conserved by strong and electromagnetic forces, could be violated by the weak interaction.

The study of strange particles, especially those called $K$ mesons of mass about 500 MeV, led in the mid-1950s to a major conundrum. Certain decay modes of $K$ mesons (now generally called *kaons*) were shown, especially by Richard Dalitz, to have opposite parity. Since this feature appeared to violate the left-right symmetry principle taken as universally valid in quantum mechanics, physicists assumed these were decay modes of different particles of very nearly equal mass. But as data accumulated, this viewpoint became hard to maintain, and C. N. Yang and T. D. Lee proposed several experiments that could be performed to determine whether parity *violation* might be a general feature of weak interactions, including pion and muon decay and $\beta$ decay. The experimental proof that this unexpected behavior was present in nature constituted the *parity revolution.*

The discovery that parity is not conserved in weak interactions, far from detracting from the significance of symmetry, actually increased interest in the discrete symmetry operators, which besides parity $P$ included charge-conjugation $C$ and time-reversal $T$. Theorists showed that relativistic locality required invariance of the Lagrangian of any system under the combined operation $CPT$. Then if invariance under time-reversal were assumed, the laws of physics would be invariant under the newly defined operation of *combined inversion* $CP$. This assumption had far-reaching consequences; for example, the neutrino turned out to have a left-handed *chirality* (i.e., handedness), while the antineutrino is right-handed.

A consequence of the neutrino's chirality was the necessary inclusion of vector ($V$) and axial vector ($A$) interactions from the five relativistic forms available for the weak interactions. This was a major step toward a truly universal weak interaction, since all weak interactions could be formulated as a mixture of $V$ and $A$, usually written as $V–A$. To complete the story required several additional steps: The interaction was formulated as that of charged *currents* (e.g., $n–p$ or $\nu–e^+$). The $V$ current was taken to be a generalized electric current (i.e., its neutral component *was* the electric current itself) and was therefore conserved; on the contrary, the $A$ current was conserved only in the limit of zero pion mass (known as partially conserved axial current, or PCAC). Finally, each current was the sum of a strangeness-conserving and a strangeness-changing part, with coefficients proportional to $\cos \theta_c$ and $\sin \theta_c$, respectively, where $\theta_c$ is the empirically determined Cabibbo angle.

During this period, the nature of the lepton sector was greatly clarified. The actual detection of the neutrino as a particle was accomplished in 1956 after years of effort by Frederick Reines and Clyde L. Cowan, Jr. Two further important results bearing on the weak interactions occurred near the end of the pions-to-quarks period. The electron and the muon were found in 1962 to be associated with distinct neutrinos, and the concept of a conserved lepton number was thus found to be valid (Schwartz, Chapter 24). And in 1964 James Cronin and Val Fitch discovered that $CP$ invariance was violated in certain rare kaon decay processes (Cronin, Chapter 7).

As noted, the detailed study of pion interactions and of the associated production and interactions of strange particles depended on the construction of multi-GeV accelerators: Brookhaven's Cosmotron (1952, 3 GeV), Berkeley's Bevatron (1954, 6 GeV), the Synchrophasotron at Dubna (1957, 10 GeV), and others.[10] In 1952 a new principle called "strong focusing" made possible the design of even more powerful accelerators. The first strong-focusing machines were electron synchrotrons (e.g., at Cornell in 1954 at 1 GeV), but the principle was soon applied also to proton accelerators, resulting in the European Center for Nuclear Research (CERN) Proton Synchrotron (1959, 28 GeV) and the BNL Alternating Gradient Synchrotron, or AGS (1960, 32 GeV). Used with the new liquid-hydrogen bubble chambers, these machines allowed a number of new resonant states to be isolated in 1960 and 1961. Bubble chambers at Brookhaven and Berkeley were used to discover strange particle resonances, both of baryonic and mesonic type. Three non-strange mesons, the $\rho(770)$, the $\omega(783)$, and the $\eta(549)$, were also observed.[11]

With these discoveries of groups of particles of given character (e.g., several isospin multiplets of the same spin and parity) emerged a new spectroscopy that various researchers then tried to analyze from the standpoint of group theory. Another approach was to develop composite models for all the hadrons. Already in 1949, Fermi and Yang had suggested that pions might be bound pairs of a nucleon and an antinucleon, and Shoichi Sakata in 1956 generalized this idea to include strangeness by taking the lambda hyperon to be a third fundamental constituent. Sakata's Nagoya associates developed this idea, pointing out that the group SU(3) was the appropriate generalization of the isospin group SU(2), which was the basis of the Fermi–Yang model.

The ultimately successful group characterization due to Gell-Mann and to Yuval Ne'eman (independently) was called the "Eightfold Way." This was also an SU(3) group characterization, but it did not require a set of observed particles to form the fundamental three-fold representation of the group. Instead, the lower-lying spin-$\frac{1}{2}$ baryons (including the nucleons) simply formed an octet representation of SU(3), while a similar octet representation was formed by the pions, the kaons, and the eta meson (hence the name Eightfold Way). This model, octet-broken SU(3), so called because the operator giving the mass differences between the isospin multiplets was assumed to transform like a member of an octet, was spectacularly confirmed by the 1964 discovery of the

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omega-minus or $\Omega^-$ particle, predicted in 1962, having three units of strangeness (Samios, Chapter 29).

### *The rise of the Standard Model*

As this third period will be the subject of the remainder of this essay, we will mention here only the most general themes and discoveries, reserving further detail for later sections. We shall for the most part refer to appropriate chapters in this book, rather than to original sources.

In the year of the $\Omega^-$ discovery, Gell-Mann and George Zweig independently proposed that hadrons could be made of three elementary fermions; not the $p$, $n$, $\Lambda$ of Sakata, but new objects having baryon number 1/3 and electric charges $e/3$ and $-2e/3$. Gell-Mann called these previously unthinkable fractionally charged objects “quarks,” and that is the name that survived. That we observe only integral multiples of the electron charge $e$ is attributed to a conjectured property of the quarks called *confinement*.

In the mid-1960s there were two rather different attitudes toward Gell-Mann's quarks (or “aces,” as they were referred to by Zweig). They were regarded, on the one hand, as useful “mathematical” constructs lacking any physical reality and, on the other hand, as real physical pointlike objects, no less real than electrons or other fermions.[12] (Gross, Chapter 11; Lipkin, Chapter 30; Morpurgo, Chapter 31; Gell-Mann, Chapter 35). These two attitudes were accompanied by successes of quark phenomenology and by unsuccessful searches for free quarks. The successes culminated in the “scaling” of structure functions observed in 1968–69 in electron–nucleon scattering at SLAC, which was interpreted as evidence for the presence within nucleons of pointlike constituents (Friedman, Chapter 32; Bjorken, Chapter 33).

It was disappointing that the formally appealing Yang–Mills theory could not be used in a straightforward manner to describe either strong or weak interactions, since that would have demanded a number of massless vector bosons that were not to be found. Even if the gauge symmetry were spontaneously broken, a theorem of Goldstone showed that the theory would always require some massless particle.[13]

However, in 1964 a method of evading Goldstone's theorem (the Higgs mechanism) made use of mixing between scalar and vector particles. It solved the mass problem for particles of spin-1 at the cost of introducing a new kind of massive particle, the spin-0 Higgs boson (Brown, Chapter 28). Steven Weinberg and Abdus Salam independently proposed a