Introduction

Overview

The Standard Model (SM) of high energy physics has been one of the great syntheses of the human intellect. It began about a century ago with the discovery of the electron, which was the first fundamental point like particle to be discovered. In the last decade, the elusive top quark and the τ neutrino have been observed. The sole remaining undiscovered particle predicted by the SM is the Higgs particle, whose vacuum field is believed to give mass to all the particles in the Universe. This text concentrates on the search for the Higgs particle at proton–(anti)proton colliders, those accelerators that collide protons and (anti)protons head on. Indeed, there are complementary efforts at electron–positron colliders, but they are outside the scope of this book.

In outline, Chapter 1 concerns itself with a summary of the Standard Model (SM), giving the particles comprising the SM and their interactions. Mathematical detail is relegated to Appendix A. Chapter 1 closes with twelve questions which are unanswered in the SM but which appear to be of fundamental importance. The next four chapters are concerned with the two initial questions that refer to electroweak symmetry breaking and the Higgs boson.

In Chapter 2 we explore a "generic" general purpose detector, which is representative of those in use at proton–(anti)proton colliders. Specifically, we examine the extent to which the SM particles introduced in Chapter 1 can be cleanly identified and measured. The accuracy with which the vector momentum and position of a SM particle can be measured is very important, as it will influence search strategies for the Higgs.

Chapter 3 is concerned with the specific issue of particle production at a proton–(anti)proton collider. The relevant formulae are given that will enable the student to estimate reaction rates for any process. In addition, the COMPHEP program can then be used to refine the initial estimates. However, students are strongly encouraged to start with the "back of the envelope" estimate before invoking COMPHEP or any other Monte Carlo program. COMPHEP is explained in Appendix B and is readily available to the student, as discussed in the section on tools below. Kinematic details are placed in Appendix C.

Chapter 4 follows up with a discussion of how recent data taken at colliders inform on the predictions of the SM. This section is a snapshot of the present state of the art in the physics of high transverse momentum phenomena as explored at proton–(anti)proton colliders.

In Chapter 5 we start to venture beyond the bounds of current data. This entire chapter is devoted to the upcoming search for the elusive Higgs boson. Much of the presentation concerns itself with the Large Hadron Collider (LHC) at the European Centre for Nuclear Research (CERN) because this facility, slated to become operational in 2007, was specifically designed to search for, and discover, the Higgs scalar (spin zero). Nevertheless, we will see that the search may be long and arduous.

Finally, in the last chapter, we return to the remaining ten fundamental questions raised in the first chapter. Some hint of theories beyond the SM and their consequences is given. In particular, the possibility is discussed that a new symmetry of Nature, a supersymmetry (SUSY) relating space-time and particle spin, might be discovered in the near future.

Scope

The mathematical complexity used here is no more than calculus. However, the concepts used require a good knowledge of quantum mechanics, special relativity and some acquaintance with field theory. Knowledge of Feynman diagrams will be essential, in part because examples of Feynman diagrams are given in the text and also because COMPHEP supplies diagrams for any process that is specified. The intended audience is then advanced graduate students or research workers in particle physics. Full theoretical rigor has, however, been sacrificed in an attempt to reach as wide and as young a group of students as possible.

Units

In this text, we will use units that are common in high energy physics. The Planck constant, $\hbar$, has the dimensions of momentum (P) times length (x) or energy (E) times time (t). (Recall the Heisenberg uncertainty relations $\Delta x \Delta P_x \geq \hbar$, $\Delta E \Delta t \geq \hbar$.) Thus $\hbar c$ has the dimension energy times length and numerically is 0.2 GeV fm. The energy unit used herein is the electron Volt (eV), the energy gained by an electron in dropping through a potential of 1 volt, and 1 GeV $= 10^9$ eV. The unit of length that is most commonly used is 1 fm $= 10^{-13}$ cm, which is the approximate size of a proton.

Other quantities with energy units are proportional to mass (m), mc^2, and momentum, cP. We adopt units with $\hbar = c = 1$. In these units, mass is given in GeV, as is momentum. For example, the proton mass is 0.938 GeV. Length, x, and ct have the dimensions of inverse energy, using $\hbar c$. We will use the notation [] to indicate the dimensions of a quantity. It should be easy for the reader to restore units by replacing P with cP, m with mc^2 and so forth.

Recall that coupling constants indicate the strength of the interaction and characterize a particular force. For example, electromagnetism has a coupling constant which is the electron charge, e, and a "fine structure" constant $\alpha = e^2 / 4\pi \hbar c$ that is dimensionless. The electromagnetic potential energy is $U(r) = eV(r) = e^2/r$ and $V(r)$ is the electromagnetic potential. The dimensions of e^2 are then energy times length, $[e^2] = [U(r)r]$, the same as those of $\hbar c$. Thus, in the units we adopt, $\hbar = c = 1$, e is also dimensionless. With $\alpha \sim 1/137$, we find $e \sim 0.303$. Coupling constants for the two other forces, the strong and the weak, will be indicated by g_i, and the corresponding fine structure constants by α_i, with $i = s, W$.

The units for cross section, σ, which we will use in this text are barns (b) (1 b = 10^{-24} cm^2). Note that $(\hbar c)^2 = 0.4$ GeV^2 mb where 1 mb = 10^{-27} cm^2. The units used in COMPHEP are pb = 10^{-12} b for cross section and GeV for energy units. As an example, at a center of mass, CM, energy, $\sqrt{s}$, of 1 TeV = 1000 GeV, in the absence of dynamics and coupling constants, a cross section scale of $\sigma \sim 1/s \sim 400$ pb is expected simply by dimensional arguments.

Tools

In this book we have extensively used a single computational tool, COMPHEP, both in the examples given in the text proper, and in the exercises. The aim was to expand the range of the text from a slightly formal academic presentation to a more interactive mode for the student, giving "hands on" experience. The plan was that the student would work the examples given in the text and the exercises and then be fully enabled to do problems on his or her own. COMPHEP runs on the Windows® platform, which was why it was chosen since the aim was to provide maximum applicability of the tool. A LINUX version is also available for students using that operating system.

The COMPHEP program is freeware. We have taken the approach in the text of first working through the algebra. That way, the reader can make a "back of the envelope" calculation of the desired quantity. Then he/she can use COMPHEP for a more detailed examination of the question. The use and description of COMPHEP is explained in detail in Appendix B, where a fully worked out example is given. A web address where the executable code (zipped) and a users' manual are available is also shown in Appendix B. The author also posts these items at uscms.fnal.gov/uscms/dgreen. Freeware to unzip files can be found at www.winzip.com/ and www.pkware.com/.

A word now about the availability of references. The use of internet archives is rather advanced in high energy physics, and we have attempted to make them easily available to the reader. The reader with Web access will have immediate access to the research literature. One of the best places to search is at the Los Alamos site, xxx.lanl.gov. Looking under "Physics" to "High Energy Physics – Experiment" (hep-ex) allows us to search on author, explore new preprints, recent preprints, or abstracts, or search in topics of our choice using the "find" feature. Many of the references cited at the end of each chapter of the text refer to this site, making the papers then directly available to the student.

Free programs to read the file formats used in archiving the research papers, .ps and .pdf, are also available on the web. For example, "pdf" files are read by freeware available at www.adobe.com/. "Postscript," or .ps, files can be read using the download from www.wisc.edu/~ghost/.

Another useful site, which is extensively quoted in the references, is the Fermilab preprint library, fnalpubs.fnal.gov, where the Fermilab references can be downloaded.

Clicking on "preprints" and then on "search" you can look for authors and/or titles and then download the full paper. An exercise is included in Chapter 1 that gives the student practice in accessing the literature.

A compendium of data in high energy physics can be found at the Particle Data Group site, pdg.lbl.gov. Finally, available at www.AnnualReviews.org are full review articles, which allow the student to explore some of the longer articles given in the references.

Our aim is obviously to make the information more immediate for the reader. In addition, some of the references given at the end of the six sections of this text are actual books. They, in turn, are rich sources of knowledge within themselves and sources of additional primary references.

1

The Standard Model and electroweak symmetry breaking

It is better to know some of the questions than all of the answers.

James Thurber

No theory is good except on condition that one use it to go on beyond.

André Gide

1.1 The energy frontier

High energy physics concerns itself with the study of fundamental particles and the interactions among them. Progress in high energy physics in the past was often due to an increase in the available energy for the production of massive particles. Since colliding two objects head-on maximizes the total center of mass (CM) energy and hence the energy available for new particle production, we specialize in this text in colliders as opposed to beams striking "fixed" targets at rest in the laboratory. We are also interested in high mass phenomena, which typically lead to particles at high momentum transverse to the axis of the colliding particles. Thus, we concentrate on the very rare high transverse momentum/energy (P_T or E_T) reactions at colliders.

In Fig. 1.1 we show the available energy for making particles as a function of the year when an accelerator began operation for the last thirty years of high energy physics research. Note the exponential increase in energy as a function of time. That increase has driven the rapid progress in the field. There are two distinct curves, one for proton–(anti)proton colliders and one for electron–positron colliders. In this text we must, in the interests of brevity, confine ourselves to the former. Also in Fig. 1.1 we show the masses of the quarks and force carriers (gauge bosons) with masses >0.1 GeV discovered over the recent past, and a schematic representation of the range of possible Higgs boson masses.

Note particularly that there has been a steady stream of discoveries of new fundamental particles of ever-heavier mass. This progression culminated recently in the discovery of the top quark, of mass 175 GeV, at Fermilab in 1996. Looking into the future, the Large Hadron Collider (LHC) at the European Centre for Nuclear Research (CERN), has been designed to fully cover the mass range where the Higgs boson is thought to exist. Note that the constituent CM energy of Fig. 1.1 is less than the proton–(anti)proton CM energy for reasons we will explain in Chapter 4 and Appendix C.

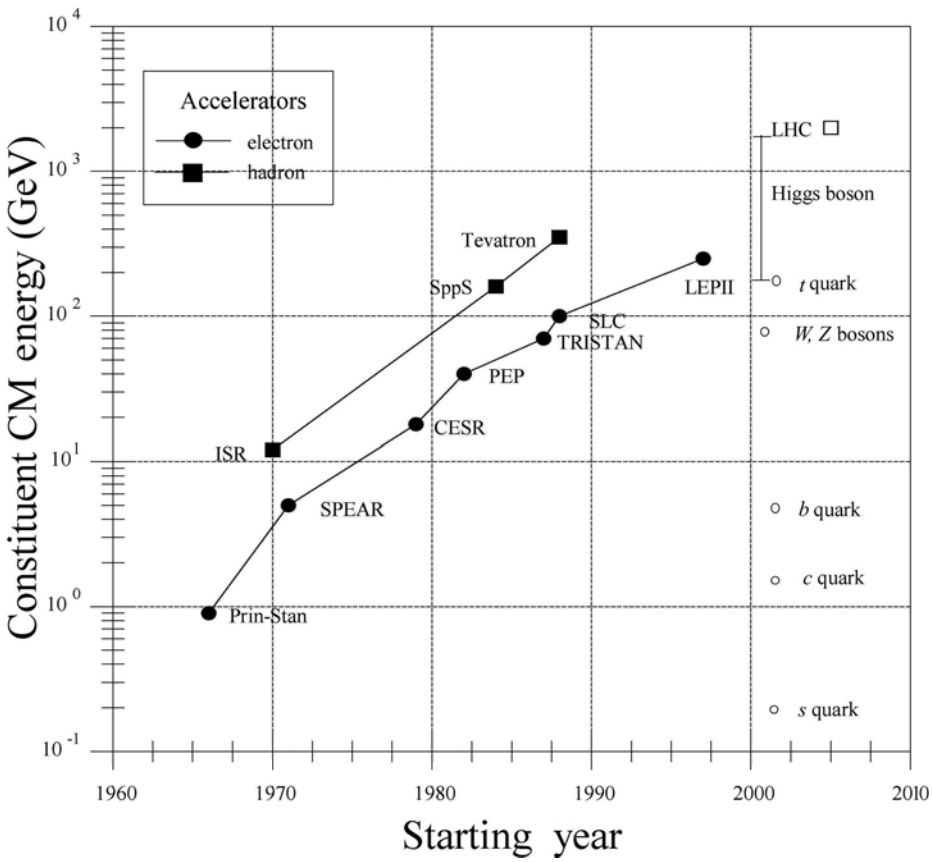

Figure 1.1 The available CM energy as a function of the year of the start of operations of an accelerator. Note the two parallel exponential trajectories for hadron, or proton–(anti)proton, and lepton, or electron–positron, colliders. The masses of the quarks and gauge bosons are also shown.

Therefore, it is timely to first briefly summarize the great accomplishment of particle physics, which is the Standard Model (SM) of fundamental processes. Following that, we can look ahead to the search for the Higgs boson, which will be made possible by yet another advance in the energy frontier.

1.2 The particles of the Standard Model

In the last century, relativity and quantum mechanics were combined together to create quantum field theory. This has led to many insights. For example, each particle is required to have an antiparticle. The first antiparticle to be discovered was the positron, the partner of the electron. In what follows we implicitly assume that each particle has an antiparticle partner, indicated as, for example, $\overline{q}$ being the antiquark partner of the quark, q.

The other great advance of the last century, General Relativity, has resisted inclusion within the SM framework. Thus, at present the SM of high energy physics does not contain gravity as a fundamental quantum theory. Clearly, then, the SM is not a complete theory of Nature.

All three of the forces found in the Standard Model are renormalizable, meaning that calculations in quantum field theory give finite results, while gravity does not. This can be anticipated by observing that classically the "fine structure" constant for gravity, α_G, increases as the square of the mass scale. This follows from noting that the gravitational potential energy, $U_G(r) = G_N M^2/r$, depends on mass, in comparison to the electrical energy, $U_{EM}(r) = e^2/r$. The quantity G_N is Newton's gravitational constant. The fine structure constants of the forces appearing in the SM, such as electromagnetism, where $\alpha = e^2/4\pi\hbar c \sim 1/137$, are dimensionless and mass independent. The gravitational analogue, $\alpha_G = G_N M^2/4\pi\hbar c$, is not.

The SM particles consist of the spin ½ (i.e. J = intrinsic angular momentum $= \hbar/2$) fermions (obeying Fermi–Dirac statistics) which are the matter particles and the spin 1 bosons (obeying Bose–Einstein statistics), which are the force carriers that communicate the forces between the fermions. A listing of these particles as understood today is given in Fig. 1.2. The strongly interacting fermions are called quarks. They are organized as "doublets" with electric charge Q/e, in units of the electron charge, e, of 2/3 and $-1/3$. The fermions with only electroweak interactions are called leptons. The uncharged leptons, which then have only weak interactions, are called neutrinos.

Let us first consider the fermions, beginning with the quarks. The lightest quarks, the up (u) and down (d) quarks, combine to form familiar bound states like the neutron (udd) and proton (uud) which are held together by the strong force. The quarks are believed to be bound permanently in the proton, say, by the strong force. Ordinary matter is made up of the u and d quarks, which comprise the first "generation." The heavier quarks have larger masses, see Fig. 1.1, but otherwise respond universally to the strong force. They are distinguished by a "flavor" quantum number, which is the weak interaction analog of "electric charge." These heavier quarks comprise the second and third generations. Particles containing strange quarks were seen in cosmic ray events in the 1950s. The charm quark (c) was discovered in 1974, the bottom (b) quark in 1977 and the top quark (t) in 1996.

The leptons are the fermions that do not have the strong "charge" (called "color") as the quarks do. The lightest charged lepton, the electron, has been known for more than a century. It was discovered by J. J. Thompson in 1896. The leptons in Fig. 1.2 are negatively charged; the electron is defined to be a particle, the positron an antiparticle. The other charged leptons appear to be simply heavier "copies" of the electron, all having the same interactions. ("Who ordered that?", as I. I. Rabi was heard to say when the muon was discovered.) The charged lepton masses for e, μ, and τ are 0.5 MeV, 0.105 GeV, and 1.78 GeV respectively. As with the quarks, the leptons comprise pairs of three recurring generations. The tau lepton was discovered in 1975.

The uncharged leptons are called neutrinos and they interact only weakly, having neither "color" nor electric charge. The radioactive "beta decay" of nuclei has also been

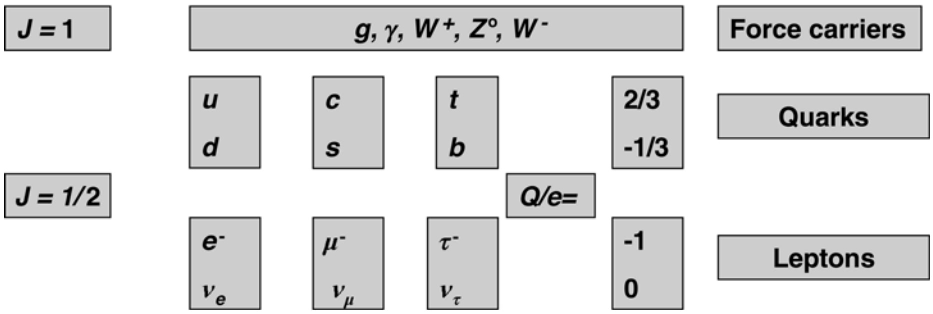

Figure 1.2 The fundamental particles of the SM. The force carriers are spin 1 bosons. The particles of matter are spin ½ fermions. The spin is indicated by the value of J, while Q/e is the electric charge in units of e.

known for a century. These decays were the first evidence for the existence of a "weak force" which caused the conversion of a proton into a neutron and a positron. Neutrinos were hypothesized to be emitted in these weak decays, $p \rightarrow n + e^+ + \nu_e$, but their very low interaction probability made their direct experimental detection a fairly recent phenomenon. The electron neutrino was observed in 1953 near a reactor which supplied a copious source of neutrinos. The tau neutrino was recently seen at Fermilab in 2000. The masses of the neutrinos are measured to be very small and for our present purposes are assigned a zero mass. We return to this topic in Chapter 6. Neutrinos also have "flavor" and come in three distinct varieties, paired to the charged leptons, as seen in Fig. 1.2.

We now turn to the force carriers of the SM. The forces are carried by vector ($J = 1$) bosons, ($[J] = [\hbar] = 1$). The massless quantum of the electromagnetic field, the photon, has also been known as a fundamental particle for almost a century following the explanation of the photoelectric effect by Einstein in 1905. The strong force is carried by massless "gluons" (g) that carry "color," the strong force analog of the charge of electromagnetism. The electromagnetic force is carried by the neutral photon (γ), and the weak force by the W^+, Z^o and W^-, which carry "flavor," the weak force analog of electric charge.

The strong force is needed to explain why the Rutherford nucleus is bound, since electrostatic repulsion of the protons in the nucleus would otherwise break it apart. Gluons were first seen experimentally in the 1970s when they were detected as radiation in electron–positron collisions yielding a quark–antiquark pair and a gluon in the final state, $e^+ + e^- \rightarrow q + \overline{q} + g$. There are eight gluons, each with a distinct color combination.

The weak force is responsible for radioactive decay, where the nuclear charge changes accompanied by the emission of an electron and an antineutrino, $n \rightarrow p + e^- + \overline{\nu}_e$. The force was initially thought to be weak because the decay rates for this "beta decay" were very slow with respect to those of electromagnetic decays. A complete understanding of the dynamics of weak interactions awaited the discovery of the W and Z bosons at CERN in 1983. The masses of the W and Z are ~80 and 91 GeV respectively. The way the W and Z obtain this mass is called "electroweak symmetry breaking" and is thought to be brought about by the "Higgs mechanism." The search for the Higgs is the central theme of this book.

The electromagnetic quantum, or photon, couples to charge, the gluons couple to "color" charge and the W and Z bosons couple to weak "flavor" charge. Gluons are "flavorblind," so all quarks dynamically interact with gluons with the same forces up to the purely kinematic effects of their different masses. The "flavor" quantum number is therefore conserved in the strong interactions, which means that heavy flavors must be strongly produced in particle–antiparticle pairs. The weak interactions are "colorblind" so that the three colors of quark all have the same weak interactions.

At this time the only undiscovered particle known to be required in the SM is the Higgs boson. This is hypothesized to be a fundamental spin 0 field quantum, one that does not appear in Fig. 1.2. It was invented to be responsible for giving mass not only to the W and Z bosons but also to the fermions of the SM. This brief introduction completes the inventory of the "periodic table" of the SM of high energy physics, indicating all the known fundamental particles.

1.3 Gauge boson coupling to fermions

So far, the SM particles have been given more or less as static objects lodged in the high energy physics "table of the elements" displayed in Fig. 1.2. To bring them to life we need to explore their dynamics. There is a great organizing principle for interactions in the SM called "gauge symmetry." We will not proceed from this first principle, but will take a short cut and move ahead by exploiting an analogy to the very successful field theory of electromagnetism. Therefore, just as in electromagnetism, we expect massless vector boson quanta universally coupled to the fermions.

Another force that is very familiar to us is gravity. General relativity asserts that physics is the same in any general coordinate system. That in turn requires the existence of a spin 2 massless "graviton" quantum coupled universally to mass with Newton's coupling constant, G_{N}.

Therefore we again, by analogy, might expect the weak and strong forces to have massless vector quanta with universal coupling. What, precisely, specifies the interaction of the bosons with the fermions? We again appeal to electromagnetism. In classical mechanics in the Hamiltonian formulation, the student has presumably seen that the free particle Hamiltonian is converted to one describing fermions interacting with photons by the replacement of the momentum $\vec{P}$ by $\vec{P} - \mathrm{e}\vec{A}$, where $\vec{A}$ is the vector potential of the electromagnetic field.

The formulation of the electromagnetic interactions in non-relativistic quantum mechanics is the same, where $P \to \mathrm{i}\hbar\partial$ is the classical to quantum replacement, as should also be familiar to the student. Therefore, to describe electromagnetic interactions the ordinary derivative ∂_μ is replaced by the "covariant" derivative D_μ in the free particle Lagrangian. The Greek subscript μ is used for indices running from 1 to 4, the standard notation for relativistic equations.

$$\partial_\mu \to D_\mu = \partial_\mu - ieA_\mu. \tag{1.1}$$

The photon then couples to all the charged pairs that exist in the SM. The fundamental interaction vertices, which appear in the Feynman diagrams, contain two fermions and a boson with a coupling strength of e in the reaction amplitude. The strength of the coupling is universal and is αQ^2 in the reaction rate, where the charge, Q, of the quark or lepton was shown in Fig. 1.2. Schematically, the photon coupling to quarks and leptons is shown in Eq. (1.2).

$$\gamma q\overline{q}, \gamma \ell^+\ell^-. \tag{1.2}$$

The strong interactions have a very similar coupling scheme for the massless colored gluons interacting with the colored quarks. The strong coupling constant is g_s, with strong fine structure constant α_s, which has a value $\sim$0.1, about 14 times larger than the electromagnetic fine structure constant, α, as befits the strong force. The Feynman vertices for the strong force have the gluon, g, coupling to quark–antiquark pairs. The amplitude is proportional to g_s. The gluon, g, coupling to quarks, q, is schematically indicated below:

$$gq\overline{q}. \tag{1.3}$$

For the weak force, there are charge changing, beta decay, interactions caused by the charged W bosons and neutral weak interactions mediated by the neutral Z. In fact, we now realize that the "weak" interactions are not intrinsically weak. They are, indeed, unified with electromagnetism and have roughly the same strength. Therefore, we speak of the unified "electroweak" force. The fine structure constant for the weak force is $\alpha_W \sim 1/30$ and the unification of the forces is embodied in the relationship $e = g_W \sin\theta_W, \alpha_W = g_W^2/4\pi$, defined by the Weinberg angle, θ_W, a quantity whose magnitude is of order one. The value of the Weinberg angle is not predicted by the SM and must be measured experimentally. It has the observed value, $\sin\theta_W = 0.475$.

The interaction vertices for the charged and neutral weak interactions are:

$$W^-q\overline{q}', W^-\ell^+\nu_\ell, Zq\overline{q}, Z\ell^+\ell^-, Z\nu_\ell\overline{\nu}_\ell. \tag{1.4}$$

In general, the W can couple to all charged quark pairs, $q\overline{q}'$. However, the most probable pairs are measured to be $W^-u\overline{d}$, $W^-c\overline{s}$, *and* $W^-t\overline{b}$. The coupling of the Z is to flavorless pairs of quarks and leptons, $\ell = e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$.

In non-relativistic quantum mechanics the reaction matrix element is the interaction potential, $V(r)$, bracketed by free plane wave initial and final states in the Born approximation. The amplitude is thus the Fourier transform of the interaction potential, $V(q)$. We appeal again to the case of electromagnetism because it should already be familiar to the student. The Coulomb potential, $V(r) \sim 1/r$, and the photon "propagator," $V(q) \sim 1/q^2$, for the massless photon should be familiar, where q is the magnitude of the difference of vector momentum between the initial and final fermion states, the "momentum transfer."