PARTICLE PHYSICS 4

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1 Introduction

Particle Physics is the field of physics that investigates Nature on the very smallest distance scales[1]. Its principal aims are:

- the identification of the most fundamental constituents of matter;
- the description of the interactions between these particles.

Thirty years ago, particle physics was still a very young and fast emerging field. Dramatic progress has been made since. A very successful *Standard Model* of Particle Physics has emerged. This theory describes with quite remarkable precision the most fundamental particles so far discovered, the *leptons* and *quarks*, both *fermions*, and their interactions via the electromagnetic, strong and weak forces through the exchange of virtual *gauge bosons*.

This course aims to describe the Standard Model of Particle Physics. It will assume that the basic concepts were described in the third year course. Based on this and on the third year quantum mechanics course we will develop methods to calculate cross sections and decay rates. The course will not follow a particular text book, but the following are a good reference:

B.R. Martin and G. Shaw: *Particle Physics* (2nd ed.), Wiley, 1997.

D.H. Perkins: *Introduction to High Energy Physics* (4th ed.), Cambridge University Press, 2000.

D. Griffiths: *Introduction to Elementary Particles*, Wiley, 1987.

F. Halzen and A.D. Martin: *Quarks and Leptons*, Wiley, 1984.

I.J.R. Aitchison and A.J.G Hey: *Gauge Theories in Particle Physics* (2nd ed.), Adam Hilger, 1989.

Review of Particle Physics, D.E. Groom *et al.*, E. Phys. J. **C15** (2000) 1.
URL: http://pdg.lbl.gov/, UK mirror at http://durpdg.dur.ac.uk/lbl/

All the books have their own merits and disadvantages. Browse these at the library. The last one is the Particle Data Group's biannually updated comprehensive source of experimental results and includes also theoretical summaries.

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[1] Since high energetic beams are often necessary to study small distances, Particle Physics is sometimes known as *High Energy Physics*. However, this definition is too narrow; it is the particles which are fundamental. In addition, many important particle physics experiments, for example, $(g-2)$ of the electron and the muon, are in fact carried out at low energy.

2 Standard Model Preview (*Third Year Review*)

In this section, the reader is presented with an overview of the current status of the Standard model. The huge experimental and theoretical efforts carried out in particle physics over the last four decades have resulted in a comprehensive description of the fundamental constituents of matter and their interactions: the Standard Model of Particle Physics.

2.1 Leptons and Quarks

The basic constituents of matter are spin 1/2 *fermions*: the **leptons** and the **quarks**. Currently, there are six known leptons which are shown in Table 1 and also six known quarks shown in Table 2. In 1897, J.J. Thomson discovered the first elementary particle: the electron (see Figure 1) which

Lepton	Symbol	Charge	Mass	Lepton Family Number		
		e	MeV/c^2	L_e	L_μ	L_τ
Electron Neutrino	ν_e	0	$< 3 \times 10^{-6}$	+1	0	0
Electron	e^-	-1	0.511	+1	0	0
Muon Neutrino	ν_μ	0	< 0.19	0	+1	0
Muon	μ^-	-1	105.66	0	+1	0
Tau Neutrino	ν_τ	0	< 18	0	0	+1
Tau	τ^-	-1	1777	0	0	+1

Table 1: Masses, charges, and additive quantum numbers of the six known leptons. The six corresponding anti-leptons with equal mass, but opposite charge and additive quantum numbers.

in today's language is called a charged lepton. The different types of charged leptons differ only in their masses; the muon is about 200 times heavier than the electron and the mass of the tau lepton is about 3500 times the electron mass.

There are two types of leptons. Each charged lepton has a *neutrino*[2] as a neutral partner. Neutrinos have no electric charge and their masses are very small. Until a few years ago, neutrino masses were consistent with zero, but recently, measurements of neutrino oscillation were reported. These results are indirect evidence for non-zero neutrino masses with mass differences $\Delta m^2 \approx 3 \times 10^{-3}$ eV^2. However, for all other purposes, neutrinos can still be treated as massless.

For each of the leptons, there also exists an *antiparticle* which has identical mass, but opposite charge and additive quantum numbers. The first known antiparticle is the anti-electron or *positron* (e^+), discovered in 1931 by Anderson (see Figure 2). Note that the anti-neutrino is a different particle than the neutrino, i.e. $\nu_e \neq \bar{\nu}_e$. In addition, each of the leptons has three additive quantum numbers, called *lepton family numbers* L_l where $l = e, \mu$, or τ. Apart from neutrino oscillations, the lepton family numbers, L_e, L_μ, and L_τ, are conserved in all reactions. For example, the muon

[2]Direct ν_τ interactions have only been observed in 2000 at Fermilab, see URL http://www-donut.fnal.gov .

decays $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ and $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ are allowed whereas the decay $\mu^+ \to e^+ \gamma$ is forbidden and has not been observed. This absence of lepton flavour violating decays is not understood.

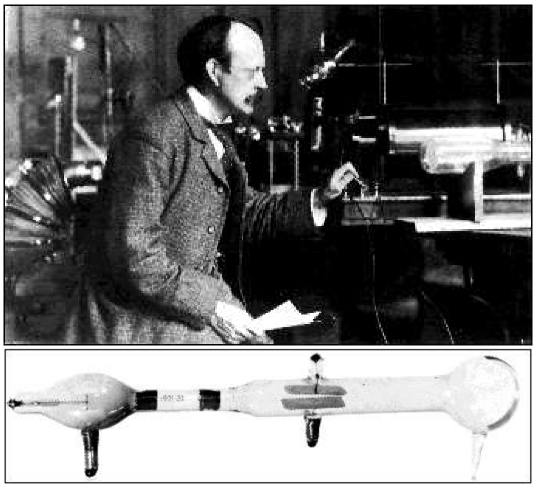

Figure 1: J.J. Thomson and apparatus for electron discovery.

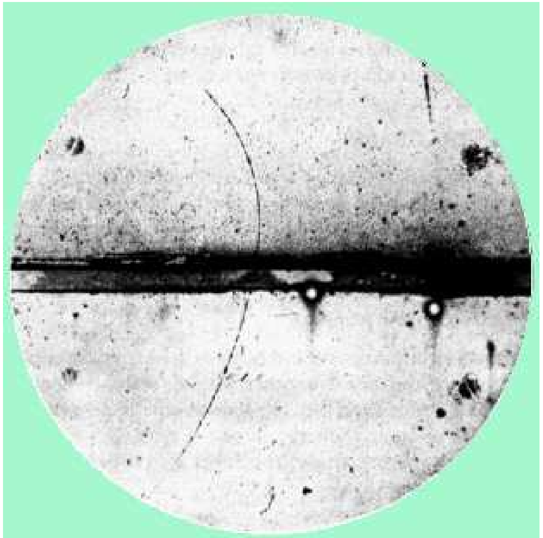

Figure 2: Discovery of positron.

Quark	Symbol	Charge e	Mass MeV/c^2	Isospin (I, I_z)	Quark Flavour Quantum Number	Baryon Number $\mathcal{B}$
up	u	+2/3	1.5 - 4.5	(1/2,+1/2)	-	1/3
down	d	-1/3	5 - 8.5	(1/2,-1/2)	-	1/3
charm	c	+2/3	1000 - 1400	-	$C = +1$	1/3
strange	s	-1/3	80 - 155	-	$S = -1$	1/3
top	t	+2/3	$(174.3 \pm 5.1) \times 10^3$	-	$T = +1$	1/3
bottom	b	-1/3	4000 - 4500	-	$B = -1$	1/3

Table 2: Mass, charged and additive quantum numbers of the six known quarks. The six corresponding anti-quarks have equal mass, but opposite charge and additive quantum numbers.

The six quarks have *fractional electric charge*. The *up-type* quarks have charge 2/3 whereas *down-type* quarks have charge -1/3. The quark masses are spread over a large range ($\mathcal{O}(1) - \mathcal{O}(10^5$ MeV/c^2). The definition of a quark mass is not unique, perturbative quark masses are used here. There are six known flavours of quarks which can be distinguished by their additive *quark flavour quantum numbers*: I (strong isospin), S (strangeness), C, B, T. Each quark has a *baryon number* $\mathcal{B} = 1/3$. For each quark there also exists its antiparticle which has identical mass and isospin, but opposite charge and additive quantum numbers. In 1995, the top quark was the last quark to be observed at the $p\bar{p}$ collider at Fermilab.

In 1964, Gell-Mann and Zweig independently proposed that all **hadrons** are composed of more elementary constituents, called quarks[3]. While leptons appear as real particles, quarks have not been measured as individual particles. Quarks remain locked inside hadrons (**Confinement**).

There are two types of hadrons: **Baryons** are bound states of three quarks For example, the proton p is a uud bound state; it has baryon number $\mathcal{B} = 1 = 1/3 + 1/3 + 1/3$ and total charge $Q = 1 = 2/3 + 2/3 - 1/3$. Analogously, the neutron is a udd bound state. **Mesons** are composed of a quark and an antiquark and have $\mathcal{B} = 0$. For example, the charged pions π^+ and π^- are $u\bar{d}$ and $\bar{u}d$ states, respectively. Using the rules of addition of angular momenta the total spin $J = 1/2$ for the nucleon and $J = 0$ for the pion can be constructed from the spin of their constituents. Baryons are fermions with half-integer spin 1/2, 3/2, 5/2, ... Mesons are bosons and have spin 0, 1, 2, ... and $\mathcal{B} = 0$.

Quarks also have a property called **colour**. Each quark comes in three primary colours, usually denoted by red, green, or blue[4]. A very important feature of colour is that all observable hadrons are "colourless" (colour singlets). Either the total amount of each colour is zero or all three colours are present in equal amounts, i.e. "white". The only combinations of quarks that can be made colourless are $q\bar{q}$ (the mesons), qqq (the baryons) and their antiparticles. Thus the proton is still a uud state but each quark has a specific colour assignment.

The colour quantum number, introduced by Greenberg in 1964, solved quite a few problems which appeared after quarks were originally proposed. Firstly, the Δ^{++} baryon, consisting of the uuu quark state, would otherwise violate the Pauli exclusion principle of fermions. Secondly, no particle made up of bound states of two quarks qq or four quarks $qqqq$ have been observed and no individual quark q has ever been found. This solution might seem farfetched but should become clearer when the *colour charge* will get a physical meaning in the context of a gauge theory.

Particle		Generations			Interactions
Quarks:	up-type down-type	$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$	$\Big\}$ electromagnetic, weak and strong
Leptons:	neutrinos charged	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$	weak weak & electromagnetic

Table 3: The three generations of quarks and leptons in order of increasing mass.

The two types of quarks and leptons are grouped in pairs: $\begin{pmatrix} u \\ d \end{pmatrix}$ and $\begin{pmatrix} \nu_l \\ l^- \end{pmatrix}$ where

[3] Gell-Mann coined the name 'quarks' in reference to the line 'three quarks for Muster Mark' in James Joyce's book 'Finnegan's wake'. Note that quark is also a German soft cheese.

[4] The term "colour" is an analogy and has of course no relation to the real colours of everyday life.

u (d) stands for a up-type (down-type) quark. Within a doublet the members differ by one unit of electric charge. In order of increasing masses each quark doublet is combined with their corresponding lepton doublet to form a family or a *generation*. The three generations are shown in Table 3. Ordinary matter, that is "our world", is built up from the members of first generation: up and down quarks form the protons and neutrons (nucleons) which together with electrons form atoms; electron neutrinos are emitted in radioactive decays, e.g. $n \to pe^-\bar{\nu}_e$. The quark and lepton doublets in the higher generations are identical to the first generation in all but one properties. They differ only in mass. Why Nature chose to proliferate and to introduce three generations is one of the major unanswered questions of particle physics.

2.2 Interactions and Gauge Bosons

Quarks and leptons interact through one of three forces: the strong, electromagnetic or weak interaction. Each of theses forces is mediated by the *virtual* exchange of a force carrying particle, a spin 1 **gauge boson**. The strong force is mediated by eight **gluons**, electromagnetic forces by the **photon**, and the weak by the *intermediate vector bosons* Z^0 and $W^\pm$. Table 4 lists the properties of these particles. Only the quarks feel the strong colour force, all charged fermions

Gauge Boson	Symbol	Charge e	Mass GeV/c^2	Interaction	Symmetry
8 Gluons	g	0	0	Strong	SU(3)
Photon	γ	0	0	Electromagnetic	U(1)
Intermediate Vector Bosons	Z^0	0	91.1876	Weak	SU(2)
	$W^\pm$	± 1	80.423		

Table 4: Properties of the gauge bosons and their interactions and underlying symmetries.

interact electromagnetically, and all fermions experience the weak force as summarized in Table 3. These interactions are often described by **Feynman diagrams** which will be discussed shortly.

The gauge bosons or *mediators* transmit the force between one quark or lepton and another. In principle the force of impact between a tennis racket and a tennis ball is nothing but the combined interaction of all leptons and quarks in one with the leptons and quarks in the other.

- The strong force between a proton and a neutron within a deuteron, say, which Yukawa took to be a fundamental process, must be regarded as a complicated interaction of six quarks mediated by the exchange of gluons. It is the strong force which holds nuclei together.

- The electromagnetic force is responsible for Chemistry. In the above example, van der Waals forces between the molecules of the tennis ball and between the molecules of the racket strings prevent the tennis ball from falling through the racket[5].

[5]and for that matter, you from falling towards the centre of the Earth.

- Radioactive decays are caused by the weak interaction, e.g. nuclear fusion processes are the energy source of our sun. Thus the sun is also prolific source of neutrinos.
- Gravity is also a fundamental interaction. It is by far the weakest known force and has no measurable effects on the scale of quarks and leptons. It can therefore be neglected.

All **electromagnetic** processes are reducible to the following elementary process: $e^- \to e^-\gamma$, shown in Figure 3. This is an example of a Feynman diagram, and it reads: An electron enters, emits or absorbs a photon and exits[6]. The probability amplitude for emitting or absorbing a photon

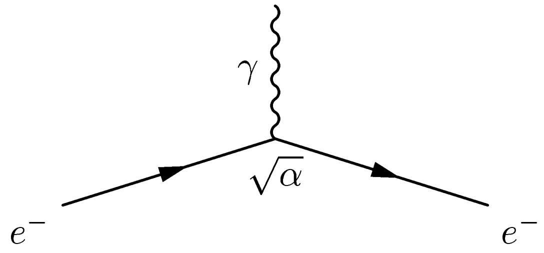

Figure 3: Feynman diagram for the electromagnetic vertex $e^- \to e^-\gamma$.

is proportional to the electron charge e and $\sqrt{\alpha}$. The coupling constant $\alpha = e^2/(4\pi\varepsilon_0\hbar c) = 1/137$ is also known as the *fine structure constant.* Here we have assumed that the charged particle is an electron, however it could be just as well a quark or any charged lepton. All other electromagnetic processes are built from this basic diagram. We simply patch together replicas of this primitive vertex. *External* lines represent observable particles, *internal* lines correspond to virtual particles. The probablity amplitude for each diagram can be calculated using the so-called **Feynman rules**.

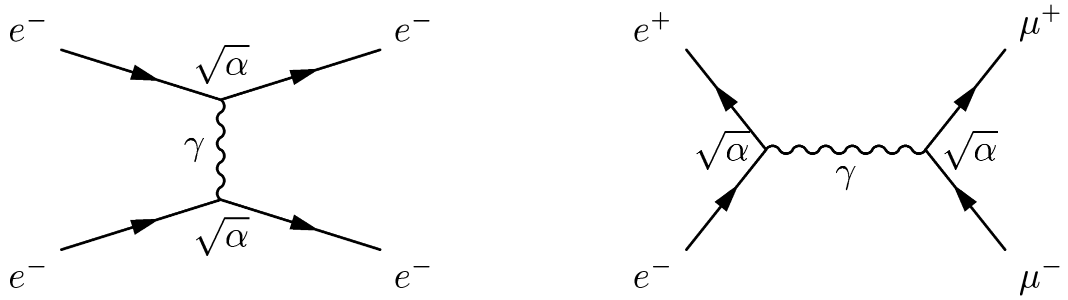

Figure 4: Feynman diagrams for the processes $e^-e^- \to e^-e^-$ and $e^+e^- \to \mu^+\mu^-$.

In Figure 4 we show the lowest order Feynman diagrams for two examples, electron-electron scattering $e^-e^- \to e^-e^-$ and electron-positron annihilation into muon pairs $e^+e^- \to \mu^+\mu^-$. But for each process also higher order diagrams with more internal vertices contribute. An example is given in Figure 5 where the photon produces a electron-positron pair which reannihilates into a photon. The actual physical process is represented by the sum of all possible Feynman diagrams.

[6]We use the convention that the time flows from left-to-right but in the literature quite often time flows upward.

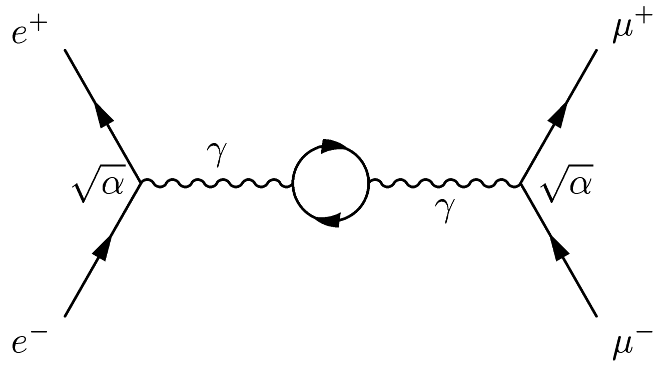

Figure 5: Vacuum polarization diagram for $e^+e^- \to \mu^+\mu^-$.

On first sight this is a huge problem: there are infinitely many diagrams for any particular reaction. Fortunately each vertex introduces a factor of α, and the numerical value of $\alpha = 1/137$ is small compared to unity. Thus higher-order diagrams contribute less and less to the final finite result; and all electromagnetic processes can be calculated based on perturbation theory. This part of the Standard model is called **quantum electrodynamics (QED)** and is a very successful theory.

For the **strong interaction** colour plays the role of the charge and the fundamental process is $q \to qg$ as shown in Figure 6. Leptons do not participate in the strong interaction. Analogous

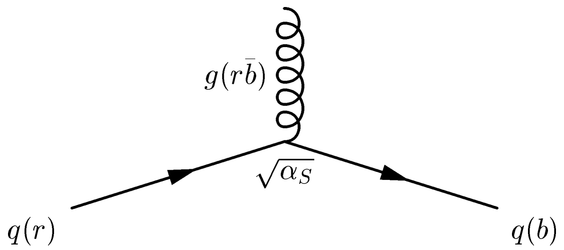

Figure 6: Feynman diagram for the process $q \to qg$.

to QED we call this theory **quantum chromodynamics (QCD)**. The probability for emitting or absorbing a gluon is proportional to the strong coupling constant α_S. At each vertex colour is conserved. Thus the gluons are bi-coloured and carry one unit of positive and one of negative colour. Since the gluons carry colour themselves – as opposed the photons which are electrically neutral – they can couple directly to other gluons and we also have fundamental three- and four-gluon vertices as shown in Figure 7.

Another difference between QCD and QED is the size of the strong coupling constant α_S. It is larger than unity. Thus more complex diagrams contribute more and more and perturbation theory breaks down at distances comparable to the size of the proton. However, it was discovered that α_S is not constant but depends on the distance between the interacting particles. We call this a "running" coupling constant. At small distances α_S becomes significantly smaller than unity, and the quarks within a proton do not interact too much. This feature is known as **asymptotic freedom** and was found experimentally in deep inelastic scattering experiments. This discovery

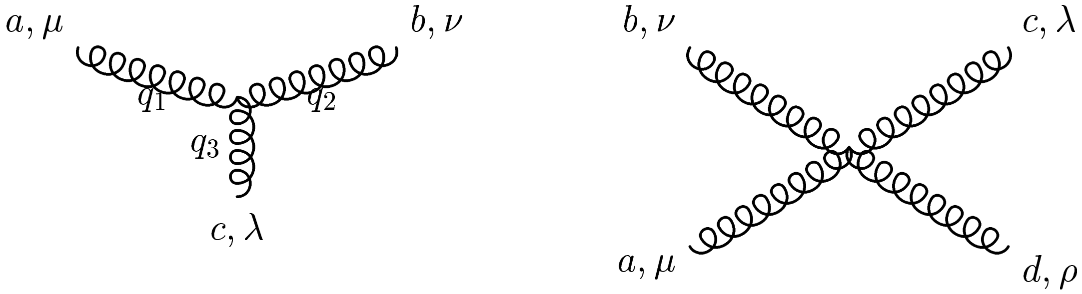

Figure 7: Feynman diagrams for 3-gluon (ggg) and 4-gluon ($gggg$) vertices.

rescued the Feynman calculus as a legitimate tool for QCD in the high-energy regime.

All fermions participate in the **weak interactions**. There are two kinds of weak interactions: **charged currents** mediated by the $W^{\pm}$ bosons and **neutral currents** mediated by the Z^0 bosons, respectively. This is shown in Figure 8. The prime examples of charged weak process

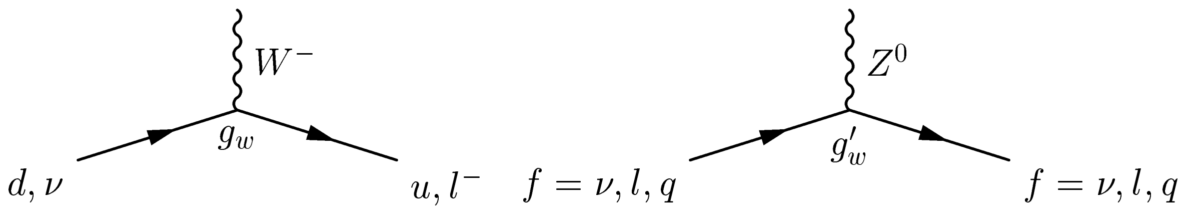

Figure 8: Feynman diagrams for the weak charged ($f\bar{f}'W^-$) and neutral currents $f\bar{f}Z^0$.

are muon decay, $\mu^- \to e^-\bar{\nu}_e\nu_\mu$, nuclear β decay, $d \to ue^-\bar{\nu}_e$, and neutron decay $n \to pe^-\bar{\nu}_e$. The strength of the weak interaction is given by the Fermi coupling constant $G_F = 1.166 \times 10^{-5}$ GeV^{-2}.

At a charged weak vertex ($f\bar{f}'W^-$), the lepton- or quark-types are changed, i.e. a neutrino is converted into a negative lepton and down-type quarks $d,\ s,\ b$ into up-type quarks $u,\ c,\ t$, respectively. For leptons, the charged weak current couples the two leptons within a doublet, but for quarks the charged current is *flavour changing* and the generations mix. This feature is represented by the *Cabibbo* angle for the first two generations and by the *Cabibbo-Kobayashi-Maskawa* matrix for three generations of quarks. Neutral currents are *flavour conserving* and were discovered at CERN in 1973 in the process $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$. As in QCD, weak three- and four-boson vertices also occur: WWZ, $WWWW$, $WWZZ$. In addition, the charged W's couple to the γ. The **flavour dynamics** of the weak interaction is based on a SU(2) symmetry.

A big success of the **Standard Model** is the **unification** of the *weak* and it electromagnetic interactions into an **electroweak theory**. The underlying *symmetry group* is:

$$SU(2) \otimes U(1)\ .$$

The **Higgs mechanism** and **spontaneous symmetry braking** allow $W^{\pm}$, Z^0, leptons and quarks to acquire mass. In 1983, the $W^{\pm}$ and Z^0 bosons were observed at CERN. We now have precise measurements of the *electroweak* parameters from e^+e^- colliders (LEP/CERN, SLC/SLAC) operating at the Z^0 resonance or above the W^+W^- production threshold.