Czech Technical University in Prague
Faculty of Nuclear Sciences and Physical Engineering

Bachelor's Thesis

Role of the Higgs Boson in the Particle Physics and his Properties

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Preface

Over the past century, there was a huge boom in particle physics discoveries. So there was a need for a theory which would describe all the phenomena appearing in the experiments. That is why the Standard Model has been formulated. The Standard Model is by now well-tested physics theory by the experiment and that is why the first chapter of this work is just about describing the Standard Model (SM) and related topics. As a bonus, the discovery of top quark in Fermilab is added as the last big verification of the SM. Nevertheless, also the SM has many problems which have to be solved. This means to extend the SM or even replace it with a more suitable and complex theory. The last chapter covers this topic.

In the Standard Model, particles gain a mass through the Higgs mechanism. According to this theory, both matter particles and force carriers acquire mass by interacting with the Higgs field. The gauge particle of this field is called the Higgs boson.

The main goal of today's particle physics is to find this particle or, if it is possible, exclude it from the Standard Model. It is why the new accelerators, such as LHC, are built and a big effort is given to this problem in the Fermilab too. Both experiments and their possible success in finding Higgs boson are described in this work.

Finally, the most common helper of an experimentalist in understanding the high-energy collisions is an event generator. For LHC and Tevatron (FNAL) Higgs search, the Pythia generator is the most suitable because of its complexity and elegancy. Nowadays, no discovery or experiment can stand without some kind of simulation. Just read the section covering this topic and you will see what the matter is.

I hope that this work can help someone, like it has helped me, to understand the beautiful small world of particles and interactions among them, as well as the future potential of presented theories and experiments.

Title:
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Abstract: The current best formulated particle theory is the Standard Model. It explains the basic phenomena of interactions between particles. To keep consistency, the Standard model requires the existence of a scalar field. Through it, the rest of the particles acquire mass. The search for a particle associated to this field - the Higgs boson - is one of the biggest efforts of today's physics. The experiments studying this topic are mainly LHC (CENR) and Tevatron (FNAL). However, the Standard model is probably not the ultimate theory. It has many unanswered questions and problems. That is why many alternative theories going beyond the Standard Model are being studied.

Key words: Higgs boson, quark, lepton, spontaneous symmetry breaking, PYTHIA.

Název práce:
Role Higgsova bosonu v současné fyzice a jeho vlastnosti

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Abstrakt: Standardní model je dnes nejpropracovanější teorií zabývající se částicemi a jejich vzájemnými interakcemi. Konzistence Standardního modelu však vyžaduje existenci skalárního pole. Interakcí s tímto polem získávají částice hmotnost. Nalézt kalibrační částici tohoto pole - Higgsova bosonu - je jedním z hlavních cílů současné fyziky. Největšími experimenty, které se touto problematikou zabývají, jsou LHC v CERNu a Tevatron ve FNALu. I přes mnohé potrvrzení Standardního modelu, i tato teorie má mnoho nezodpovězených otázek a problémů. Proto vznikají a studují se i další teorie jdoucí za hranice Standardního modelu.

Klíčová slova: Higgsův boson, kvark, lepton, spontánní narušení symetrie, PYTHIA.

Contents

Chapter 1

Introduction to the Standard Model

1.1 Basics of the Standard Model

The unifying theory which attempts to explain all the phenomena of particle physics in terms of the properties and interactions of a small number of particles is called **the Standard Model.**

All known particles can be divided into three groups: leptons, quarks and gauge bosons. These particles interact with each other through 3 interactions known in the standard model - electromagnetic, weak and strong interaction. In addition, there is a fourth force of nature - gravity which has not been included into the standard model (yet).

Leptons are spin-$\frac{1}{2}$ fermions which are assumed to be elementary - no inner structure or excited states. The most familiar example of lepton is the electron or neutrino.

Quarks are also spin-$\frac{1}{2}$ fermions and form particles called hadrons and mesons.

Gauge bosons are elementary spin-1 bosons which act as "force carriers" in the theory.

Electromagnetic interaction bound electrons in atoms and other interaction between two charges. Force carriers are massless photons γ and resulting force is long-range.

Weak interaction is the force responsible for the b-decay of nuclei. Force carriers are very massive $W^{\pm}$ and Z bosons and the interaction is short-range.

Strong interaction holds together hadrons and mesons which are built by quarks. It bounds also nucleons into nuclei. Force carriers are massless gluons g.

1.2 Leptons

Leptons are one of the three classes of particles in the standard model. There are six known leptons and they occur in pairs called generations which are written as **doublets:**

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \tag{1.1}$$

The three charged leptons (e^-, μ^-, τ^-) are the familiar electron and two new particles, the mu-lepton or **muon** and the tau-lepton or **tauon**. All have charge of Q $= -e$. Associated with them in doublet are three neutral leptons - neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ called **the electron neutrino, muon neutrino** and **tauon neutrino** respectively, which all have very small masses. In addition to the leptons there are six corresponding antiparticles (**antileptons**):

$$\begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix} \quad \begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix} \tag{1.2}$$

The charged leptons interact via both electromagnetic and weak forces, whereas for neutral leptons only weak interaction has been observed. Next, I would like to point out that each generation of leptons shows conservation of quantum number in all known reactions. The first of these **lepton numbers** is the **electron number** defined for any state as:

$$L_e = N(e^-) - N(e^+) + N(\nu_e) - N(\bar{\nu}_e) \tag{1.3}$$

where $N(e^-)$ is the number of electrons present in reaction and so on. In electromagnetic interactions, electron number conservation reduces to the conservation of $N(e^-) - N(e^+)$, since neutrinos are not involved. This implies that electrons and positrons can only be created or annihilated in pairs. In weak interactions more general possibilities are allowed. For example, an electron can be created together with an antineutrino $\bar{\nu}_e$, rather than a positron. As a electron number is conserved in all known reactions, the same can be applied to **muon number** and **tauon number**:

$$L_\mu = N(\mu^-) - N(\mu^+) + N(\nu_\mu) - N(\bar{\nu}_\mu) \tag{1.4}$$

$$L_\tau = N(\tau^-) - N(\tau^+) + N(\nu_\tau) - N(\bar{\nu}_\tau) \tag{1.5}$$

1.2.1 Electron and its neutrino

We have already classified the electron ($m_e = 0,511 MeV/c^2$) so it is time to move on to its partner - electron neutrino. The existence of the **electron neutrino** ν_e was first postulated by Pauli in 1930 in order to understand the observed β-decays:

$$(Z, A) = (Z + 1, A) + e^- + \bar{\nu}_e \tag{1.6}$$

$$(Z', A') = (Z' - 1, A') + e^+ + \nu_e \tag{1.7}$$

where (Z, A) denote the atomic and mass numbers respectively. These reactions are actually decays of bound neutrons and protons via the basic processes:

$$n \to p + e^- + \bar{\nu}_e \tag{1.8}$$

$$p \to n + e^+ + \nu_e \tag{1.9}$$

where only the neutron decay can occur in free space since $m_n > (m_p + m_e)$. The neutrinos are usually inferred from energy and angular momentum conservation. In case of energy, if the antineutrino were not present in (1.6), the reaction would be a two-body decay and the energy E_e of the emitted electron would have the unique value

$$E_e = \Delta M = M(Z, A) - M(Z + 1, A) \tag{1.10}$$

where we have neglected the nuclear recoil energy. However, if the antineutrino is present, the electron energy will not be unique, but it will lie in the range

$$m_e \leq E_e \leq (\Delta M - m_{\nu e}) \tag{1.11}$$

Experimentally, the observed spectrum spans the whole range (1.11) with the mass of the electron neutrino approximately zero.

1.2.2 Further generations

The next leptons we have mentioned are muon μ, tauon τ and its associated muon neutrino ν_μ and tauon neutrino ν_τ respectively. Let's look at them in detail.

The muon is a very penetrating particle of mass $105,7MeV/c^2$ which was first identified in cosmic ray experiments by Anderson and Neddermeyer in 1936. Cosmic ray primaries are high-energy particles, mostly protons, incident on the earth's atmosphere from all directions in space. Other particles, called secondaries, are produced when the primaries collide with nuclei in the earth's atmosphere, and some penetrate to sea level. It was among these that muons were discovered. In time, they have been produced at accelerator laboratories, enable to study them in great detail.

Muons are point-like spin-$\frac{1}{2}$ and in general their electromagnetic properties are identical with those of electrons, provided the mass difference! More clearly - muon mass is much greater than electron's. This is the reason for their much greater penetrating power in matter compared with electrons, because high-energy electrons lose energy in matter dominantly by radiative collisions [24] which is proportional to m^{-2}. Consequently, muon travel much further in matter.

The tauon is even heavier ($m_\tau = 1777MeV/c^2$) and was discovered in electron-positron annihilation experiments at high energies in 1975. Its properties have been measured less precisely than those of the muon, bud are compatible with a point-like spin-$\frac{1}{2}$ particle whose electromagnetic interactions are identical with those of the electron and muon.

1.2.3 Lepton decays

Because the electron is the lightest charged particle, conservation of electric charge means it is necessarily stable. However, both the muon and the tauon are unstable with lifetimes $2.2 \times 10^{-6}s$ and $2.9 \times 10^{-13}s$ respectively. Both decay by weak interactions and the great difference in their lifetimes is a result of the mass difference. In the case of muon, the decay is purely leptonic:

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \tag{1.12}$$

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu \tag{1.13}$$

and conserves both charge and lepton number.

For the tauon, many decay modes are observed, most of them involving hadrons in the final state. However, purely leptonic modes are also observed:

$$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau \tag{1.14}$$

$$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau \tag{1.15}$$

As was said before, neutrinos emitted in the decays are inferred form energy and angular momentum conservation. However, the muon neutrino ν_μ has been detected in other reactions. Well-defined muon neutrino beams can be created in the laboratory and used to study reactions like inverse muon decay

$$\nu_\mu + e^- \to \mu^- + \nu_e \tag{1.16}$$

and other neutrino scattering processes like

$$\nu_\mu + n \to \mu^- + p \tag{1.17}$$

The tauon neutrino has never been detected in this way and the evidence for its existence rests entirely on energy and angular momentum conservation. The masses of both ν_μ and ν_τ can be inferred from the e^- and μ^- energy spectra in the decays (1.12) – (1.15) using energy conservation. The present properties of leptons are in Table 1.1.

Particle	**Mass**	**Mean life**
ν_e	$< 2.3eV$	stable
ν_μ	$< 0.17MeV$	stable
ν_τ	$< 18.2MeV$	stable
$e^\pm$	$0.511MeV$	stable
$\mu^\pm$	$105.658MeV$	$2.197 \times 10^{-6}s$
$\tau^\pm$	$1777.0MeV$	$2.910 \times 10^{-13}s$

Table 1.1: Properties of leptons

1.3 Quark Model

1.3.1 Introduction

Quarks and their bound states - hadrons are strongly interacting particles. These also interact by the weak and electromagnetic interactions, however such effects can often be neglected compared with the strong interactions.

Strong interactions are most familiar in nuclear physics, where the interactions of neutrons and protons are studied at relatively low energies of a few MeV. However, in 1947, new types of hadrons, not present in ordinary matter, were discovered in cosmic rays by groups from the universities of Bristol and Manchester. To create these new particles required high energies, in accordance with Einstein's mass-energy relation $E = mc^2$, and as intense beams of particles of increasingly high energies became available at accelerator laboratories, more and more hadrons were discovered. By the late 1960s several dozens were known, and some unifying theoretical framework was urgently needed to interpret this multitude of states if any progress was to be made. The result was the **quark model**. In 1964, Gell-Mann, and independently Zweig, noted that all the observed hadrons could be simply interpreted as bound states of just three fundamental spin-$\frac{1}{2}$ particles, together with their antiparticles. These particles were required to have fractional electric charges of $\frac{2}{3}$ and $\frac{1}{3}$ in units of e and were called quarks by Gell-Mann.

In the following years, the success of the quark model grew ever more impressive as more and more states were discovered. Nonetheless, the existence of quarks as real particles, rather than convenient mathematical entities, was seriously doubted because all attempts to detect free quarks, or any other fractionally charged particles, met with failure. These doubts were subsequently removed in two ways. Firstly, a series of experimental results, starting in 1968 with the scattering of high-energy electrons from protons, showed the dynamical effects of individual quarks within the proton. Secondly, a detailed theory of strong interactions was constructed, which both successfully described the experimental results and offered an explanation of why isolated free quarks could not be observed. This theory is called Quantum Chromodynamics (QCD). As a result of these developments the quark hypothesis is now universally accepted and is central to the interpretation of a wide range of phenomena in particle physics.

1.3.2 Quarks

In modern particle physics, the symmetry and the constituent of matter having its symmetry are powerful tools to understand the structure of matter and its physics. One such example is the proton and neutron which are the constituents of all nuclei and possess the $SU(2)$ symmetry of isospin. Various properties of nuclei are well understood by the dynamics of protons and neutrons having the $SU(2)$ symmetry of isospin.

For our purpose, it is better to use "similar" procedure proposed by Gell-Mann and Zweig. They constructed model of hadrons - the quark model - in which the hadrons are beautifully classified with the $SU(3)$ symmetry.

In 1950s, new hadrons were discovered. Those new hadrons were surprisingly long-lived compared to the strong interaction scale. For example, the Λ^0 and K^0 are easily produced in high energy $\pi^- p$ scattering, but those particles decay into light hadrons with very long lifetime

$$\pi^- + p \rightarrow \Lambda^0 + K^0 \tag{1.18}$$

$$\begin{aligned} \Lambda^0 &\rightarrow p + \pi^- \\ K^0 &\rightarrow \pi^+ + \pi \end{aligned} \tag{1.19}$$

To explain the fact that while the production of Λ^0 and K^0 occurs with strong interaction scale, the decay of those particles does with weak interaction scale, Nakano and Nishijima and, independently, Gell-Mann introduced a new additive quantum number called **strangeness (S)** (discussed in next section). They assigned $S = 0$ for p, π^-; $S = +1$ for K^0 and $S = -1$ for Λ^0 and considered that while the strong interaction conserves the quantum number S, the weak interaction does not. In the production process (1.18), S is conserved, but in the decay processes (1.19) it is not. Soon later, the idea of Nakano, Nishijima and Gell-Mann was confirmed from observed properties of many strange particles discovered those days. The conservation of the strangeness S is similar to the one of the charge Q due to the $U(1)$ electromagnetic symmetry. This suggests the existence of a new $U(1)$ symmetry. Actually there can be introduced the symmetry called the $U(1)$ hypercharge symmetry, where the new quantum number **Y - hypercharge -** is defined by the sum of the baryon number B and strangeness S ($Y = B + S$).

Because of this new $U(1)$ symmetry, the strong interaction conserves the hypercharge Y and hence, the strangeness S is also conserved in strong interactions, because the baryon number B is a good quantum number for the strong interaction. Then, we can see that the following relation, being called the Nakano-Nishijima-Gell-Mann (NNG) relation

$$Q = I^3 + \frac{Y}{2}, \tag{1.20}$$

works well for all hadrons discovered those days, where Q and I^3 are the charge and the 3^{rd} component of the isospin of the hadron, respectively.

In 1964, Gell-Mann and Zweig introduced the quarks as physical substances to realize the relation (1.20). In the quark model, all hadrons are made of a few quarks. While all **baryons** are made of 3 quarks, all **mesons** are made of a quark q and an antiquark $\bar{q}$, where all quantum numbers of $\bar{q}$ is opposite to those of q. Since the quark model should make even strange hadrons like Λ^0 and K^0, we need a new quark, i.e. the s (**strange**) quark in addition to the u (**up**) and d (**down**) quarks which nicely build the non-strange hadrons like p, n, π, etc. Thus, in the original quark model the u, d and s quarks were considered to be the fundamental constituents of hadrons and to have the $SU(3)$ symmetry. This symmetry is not perfect because of the mass differences of strange quark and non-strange quarks. Later, the existence of more heavier quarks c (**charm**), b (**bottom**) and t (**top**) quarks were also established. Now, we have 6 different kinds of quarks q_i $(i = u, d, s, c, b, t)$ and these degree of freedom is called "**flavour**", which is unrelated to another degree of freedom "**colour**", being the strong interaction charge which plays an important role in the **quantum chromodynamics** (QCD), the field theory of strong interactions. All known quarks with their quantum numbers and properties are in Table 1.2.

Name	Symbol	Mass	Q	I_3	S	C	$\tilde{B}$	T
down	d	$3 \sim 9MeV$	$-\frac{1}{3}$	$-\frac{1}{2}$	0	0	0	0
up	u	$1.5 \sim 5MeV$	$+\frac{2}{3}$	$+\frac{1}{2}$	0	0	0	0
strange	s	$60 \sim 170MeV$	$-\frac{1}{3}$	0	-1	0	0	0
charmed	c	$1.47 \sim 1.83GeV$	$+\frac{2}{3}$	0	0	+1	0	0
bottom	b	$4.6 \sim 5.1GeV$	$-\frac{1}{3}$	0	0	0	-1	0
top	t	$178.1^{+10.4}_{-8.3}GeV$	$+\frac{2}{3}$	0	0	0	0	+1

Table 1.2: Quarks and their quantum numbers

By taking into account quark quantum numbers, we can make many hadrons from those quarks like p = (uud), n = (udd), $\Lambda^0 = (uds)$, $\pi^+ = (u\bar{d})$, $\pi^- = (\bar{u}d)$, $K^0 = (d\bar{s})$, *etc.*

In the $SU(3)$ symmetric world, the fundamental representation of the quark is given by the triplet (=**3**)

$$q = \begin{pmatrix} u \\ d \\ s \end{pmatrix} \tag{1.21}$$

Here, it is considered an idealized world of equal quark masses of u, d and$s$, though they are, in fact, different. Therefore, the same mathematics can be applied for the color $SU(3)$, which is an exact symmetry. The $SU(3)$ includes the $SU(2)$ of isospin and the $U(1)$ of hypercharge as subgroups. Then, it is possible to plot the members of the quark triplet with their quantum numbers of I^3 and Y in (I^3, Y) space, as shown in Figure 1.1a). The members of the antiquark triplet (=**3***) are also plotted - in Figure 1.1b). Figure 1.1 is called the **weight diagram.**

Representations of mesons and baryons

In the quark model, mesons are composed of $q\bar{q}$, while baryons are of qqq (antiquarks in case of anti-baryons). Therefore, it is interesting to see the product of representations of the $SU(3)$ group. If some representations of the group can be decomposed into a direct sum of other independent representations, they are called "**reducible**" and if not, they are called "**irreducible**". The whole mathematical apparatus is shown in group theory and $SU(3)$ decompositions

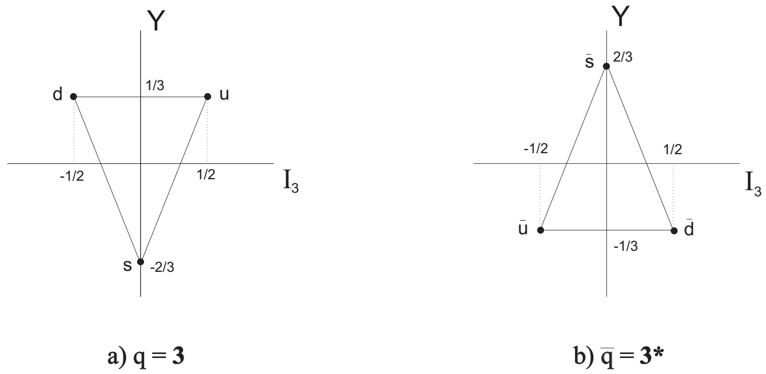


Figure 1.1: Weight diagram for $q = \mathbf{3}$ and $\bar{q} = \mathbf{3^*}$

are well-described by the simple Yang tableaux. Or just in simple cases this relation can be used [10]

$$N \otimes \overline{N} = 1 \oplus N^2 - 1$$
$$N \otimes N = \overline{\frac{N(N-1)}{2}} \oplus \frac{N(N+1)}{2}$$

So now let´s show direct product $\mathbf{3} \otimes \mathbf{3^*}$

$$\mathbf{3} \otimes \mathbf{3^*} = \mathbf{8} \oplus \mathbf{1} \tag{1.22}$$

Next, consider the direct product $\mathbf{3} \otimes \mathbf{3}$. It is also reducible

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{3^*} \oplus \mathbf{6} \tag{1.23}$$

$\mathbf{3^*}$ and $\mathbf{6}$ do not mix under the $SU(3)$ transformation and each one cannot be decomposed any more. They are irreducible.

Finally, by multiplying one more quark state to (1.23), one can obtain the final decomposition of qqq states as

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = (\mathbf{3^*} \oplus \mathbf{6}) \otimes \mathbf{3} = (\mathbf{3^*} \otimes \mathbf{3}) \oplus (\mathbf{6} \otimes \mathbf{3}) = \mathbf{1} + \mathbf{8}_A + \mathbf{8}_S + \mathbf{10} \tag{1.24}$$

where the first 2 quarks are antisymmetric and symmetric in 8_A and 8_S, respectively.

Applying this results we can get for example **pseudoscalar mesons** - by using (1.22) and weight diagrams in Figure 1.1 one can get mesons with $J^P = 0^-$ (Figure 1.2) just by graphically multiplications of the weight diagrams.

A fourth quark, such as charm c, can be included by extending $SU(3)$ symmetry to $SU(4)$. However, $SU(4)$ is "badly broken" because of the much heavier c quark. The weight diagrams for the ground-state pseudoscalar ($J^{PC} = 0^{-+}$)

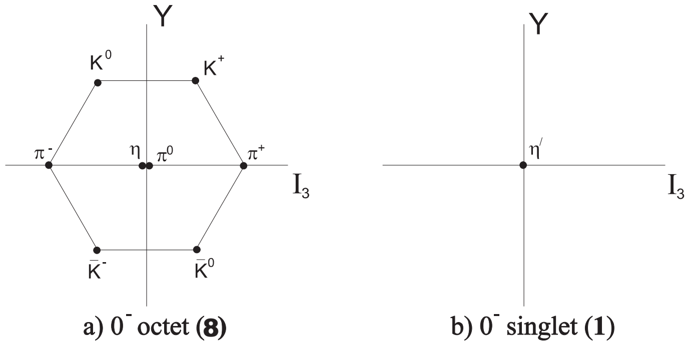


Figure 1.2: Mesons in the quark model

and vector (1^{--}) mesons are shown in Figure 1.4.

Applying (1.24), one can get **baryon** representation, which is shown in Figure 1.3 - again using weight diagrams from Figure 1.1.

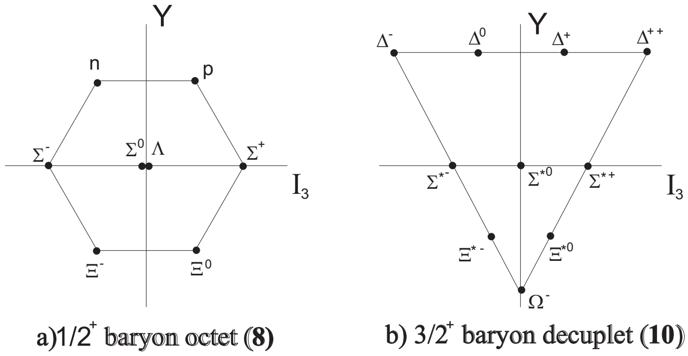


Figure 1.3: Baryons in the quark model

The addition of the c quark to the light quarks extends the flavour symmetry. Figure 1.5 show the $SU(4)$ baryon multiplets that have at their bottom levels an $SU(3)$ octet, such as the octet that includes the nucleon, or an $SU(3)$ decuplet, such as the decuplet that includes the $\Delta(1232)$. All the particles in a given $SU(4)$ multiplet have the same spin and parity. The addition of a b quark extends the flavour symmetry to $SU(5)$ - it would require four dimensions to draw the multiplets.

The top quark is too unstable to form observable hadron states and its inferred from its decay products. More information about top quark will be added in further sections. None of the masses can be obtained from measurements on isolated free quarks because free quarks have never been seen despite many experiments to find them (free quarks would be most probably identified via their fractional electric charge - but no one measures it).

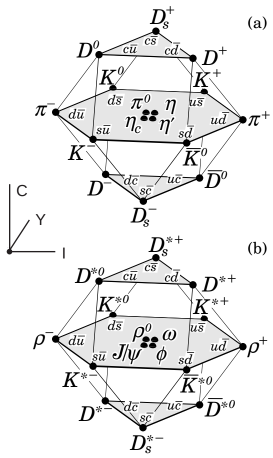


Figure 1.4: SU(4) weight diagram showing the 16-plets for the pseudoscalar (a) and vector mesons (b) made of the u, d, s and c quarks as a function of isospin I, charm C and hypercharge $Y = S + B - \frac{C}{3}$. The nonets of light mesons occupy the central planes to which the $c\bar{c}$ states have been added.

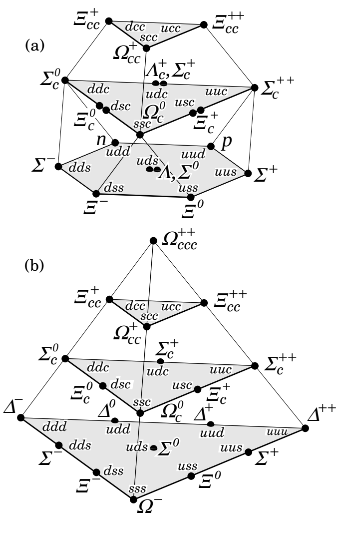


Figure 1.5: SU(4) multiplets of baryons made of u, d, s and c quarks. a) The 20-plet with an $SU(3)$ octet. b) The 20-plet with an $SU(3)$ decuplet.

1.3.3 General properties of hadrons

Although no isolated quarks have been found, more than two hundred of their bound states have been discovered - all with integer electric charges. The reason for this is closely associated with a new degree of freedom which exists for quarks, but not for leptons, called **colour.** Only three types of quark bound states are allowed. These are the baryons, which have half-integer spin and are assumed to be bound states of three quarks ($3q$), the antibaryons ($3\bar{q}$) which are antiparticles to baryons and the mesons, which have integer spin and are assumed to be bound states of a quark and an antiquark ($q\bar{q}$).

Hadrons			
Particle	**Quark content**	**Mass**	**Mean lifetime**
p	uud	$938.2723(\pm 3)MeV$	$> 1.6 \times 10^{23} yr$
n	udd	$939.5656(\pm 3)MeV$	$887s$
Λ	uds	$1115.684MeV$	$2.63 \times 10^{-10}s$
Λ_c^+	udc	$2284.9MeV$	$2.1 \times 10^{-13}s$
Mesons			
Particle	**Quark content**	**Mass**	**Mean lifetime**
π^+, π^-	$ud, d\bar{u}$	$139.5700MeV$	$2.6033s$
π^0	$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	$134.9764MeV$	8.4×10^{-17}
K^+, K^-	$d\bar{s}, s\bar{d}$	$493.68MeV$	1.239×10^{-8}

Table 1.3: Examples of baryons and mesons with their properties

All hadrons have several quantum numbers which are associated with any state and which refer to its quark content. Now they will be defined:

Strangeness S

$$S = -N_s = -[N(s) - N(\bar{s})] \tag{1.25}$$

where $N(s)$ and $N(\bar{s})$ are the number of s quarks and $\bar{s}$ antiquarks present in the state. Clearly $S = -1$ for an s quark. $S = 1$ for an $\bar{s}$ antiquark and $S = 0$ for all other quarks and antiquarks. The **charm C**, **beauty** $\tilde{B}$ and **truth T** quantum numbers are similarly defined by

$$\begin{aligned} C &= N_c &&= N(c) - N(\bar{c}) \\ \tilde{B} &= -N_b &&= -N(b) - N(\bar{b}) \\ T &= N_t &&= N(t) - N(\bar{t}) \end{aligned} \tag{1.26}$$

The last number to discuss here is **baryon number B** defined as:

$$B = \frac{1}{3}(N_u + N_d - S + C - \tilde{B} + T) \tag{1.27}$$

These quantum numbers are important, because in strong and electromagnetic interactions quarks and antiquarks are only created or destroyed in particle-antiparticle pairs. For example,the quark description of the strong interaction process

$$p + p \rightarrow \Lambda^0 + K^+ + p^+ \tag{1.28}$$

is

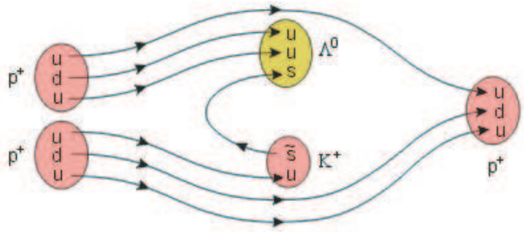


Figure 1.6: Proton proton collision

On counting the quarks of each flavour, we can see that the final state contains the same number of quarks of each flavour as the initial state, plus an additional $s\bar{s}$ pair, so that the quark numbers N_u and N_s are separately conserved. This is characteristic of *strong* and *electromagnetic processes,* in which all the quark numbers (1.25), (1.26) and (1.27) are separately conserved.

However in neutron beta-decay

$$n \to p + e^- + \bar{\nu}_e \tag{1.29}$$

where,in quark interpretation, a d quark is replaced by a u quark and N_u and

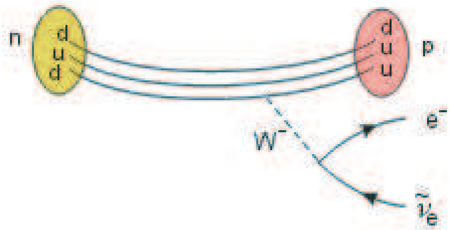


Figure 1.7: Neutron beta decay

N_d are not conserved. This is characteristic for the *weak interaction,* in which the quark flavours can change, and only baryon number (1.27) and the total electric charge are in general conserved.

The quark numbers (1.25), (1.26) and (1.27) play an important role in understanding the long lifetimes of some hadrons. The vast majority of hadrons are highly unstable and decay to lighter hadrons by the strong interaction with lifetimes of order $10^{-23}s$. However, each hadron is characterized by a set of values for $B, Q, S, C, \tilde{B}$ and T, and in some cases there are no lighter hadron states with the same values of these quantum numbers to which they can decay. These hadrons, which cannot decay by strong interactions, are long-lived on a timescale of order 10^{-23}s and are often called *stable particles* or *long-lived* particles. Electromagnetic decay rates are suppressed by powers of the fine structure constant α relative to strong decays, leading to observed lifetimes in the range

$10^{-16}s$ – $10^{-21}s$. Weak decays give longer lifetimes which depend sensitively on the characteristic energy of the decay. The typical lifetimes corresponding to each interaction are summarized in Table 1.4.

Interaction	**Lifetime [s]**
Strong	$10^{-22} - 10^{-24}$
Electromagnetic	$10^{-16} - 10^{-21}$
Weak	$10^{-7} - 10^{-13}$

Table 1.4: Typical lifetimes of hadrons decaying by the three interactions

1.3.4 Lightest hadrons

The lightest known mesons are the **pions** or pi-mesons $\pi^{+-}(140)$, $\pi^0(135)$ where masses are indicated in brackets in MeV/c^2. Their quark constitution are

$$\begin{aligned} \pi^+ &= u\bar{d} \\ \pi^0 &= u\bar{u}, d\bar{d} \\ \pi^- &= d\bar{u} \end{aligned} \tag{1.30}$$

These particles are produced in many hadronic reactions which conserve both charge and baryon number. For example

$$p + p \rightarrow p + n + \pi^+ \tag{1.31}$$
$$\rightarrow p + p + \pi^0 \tag{1.32}$$
$$\rightarrow p + p + \pi^+ + \pi^- \tag{1.33}$$

The charged pions decay predominantly by the reactions

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \end{aligned} \tag{1.34}$$

with lifetimes $2.6 \times 10^{-8}s$, typical for weak interactions. They were first discovered in cosmic rays by a Bristol group in 1947 using photographic emulsions containing a silver halide.

Neutral pions were discovered somewhat later and decay by the electromagnetic interaction

$$\pi^0 \rightarrow \gamma + \gamma \tag{1.35}$$

with a lifetime $0.8 \times 10^{-16}s$. Because they are neutral they do not leave tracks and must be detected via their decay photons.

Pions play an important role in nuclear forces. In 1935 Yukawa proposed that these were due to the exchange of spin-0 mesons, and from the range of the forces (which was not precisely known at that time) predicted that these mesons should have a mass of approximately $200MeV/c^2$. This discovery of pions was a great triumph for the Yukawa theory. In it, the nuclear forces are given by Figure 1.8, where the nucleons and pions are treated as point particles. Neutral pion exchange gives rise to normal direct forces, while π^{+-} exchange gives rise to exchange forces where neutron and proton are exchanged.

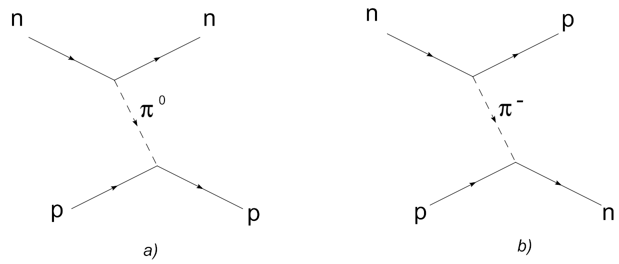


Figure 1.8: Yukawa model for nuclear forces: a) direct forces, b) exchange forces

The lightest known baryons are nucleons. The quark combinations for nucleons are

$$p = uud \quad (1.36)$$
$$d = udd \quad (1.37)$$

which are given by their electric charges.

1.3.5 Heavier hadrons - charm and beauty

Soon after the discovery of the pion, member of the Manchester cosmic ray group discovered other mesons and baryons which were produced in strong interactions, but decayed by weak interactions. This was unexpected, as there was apparently no reason why they should not decay by the strong interactions with lifetimes of order $10^{-23}s$. For this reason they were named "**strange particles**". One of the first observed events was $\mathbf{K}^{+}$ meson (kaon) decay. ($m_{K^+} = 494MeV/c^2,\ \tau_{K^+} = 1.0 \times 10^{-8}s$). Charged kaons have many decay modes, but the principal ones and their branching ratios are

$$K^+ \rightarrow \mu^+ + \nu_\mu,\ B = 0.64 \quad (1.38)$$
$$\rightarrow \pi^+ + \pi^0,\ B = 0.21 \quad (1.39)$$

Another example of a strange particle is the Λ (lambda) baryon, which has a mass of $1116MeV/c^2$ and decays mainly into pions and nucleons

$$\Lambda \rightarrow \pi^- + p,\ B = 0.64 \quad (1.40)$$
$$\rightarrow \pi^0 + n,\ B = 0.36 \quad (1.41)$$

with a lifetime of $2.6 \times 10^{-10}s$.

It is clear from the long lifetimes of the K^+ and Λ that they both decay via the weak interaction. This strongly suggests that these particles are not made of u and d quarks alone. Since if this were the case then, for example, the neutral Λ would be a (udd) state just like the neutron. At a quark level, the decay (1.40) would then be

$$(udd) \to (d\bar{u}) + (uud),$$

which conserves the u and d quark numbers. We would therefore expect (1.40) to be a strong decay, with a lifetime of order $10^{-23}s$, in contradiction to experiment. The solution is to assign the quark structure uds to the Λ, so that the decay (1.40) is

$$\begin{array}{lcccc} & (uds) & \to & (d\bar{u}) + (uud) & \\ S: & -1 & \neq & 0 \qquad 0 & \end{array} \tag{1.42}$$

and neither the quark number N_d nor the strangeness S is conserved. As both the strong and electromagnetic interactions conserve all quark numbers, the decay can only go by the weak interaction, in which such quark numbers are not conserved.

Strange particles are now defined as any particle with a non-zero value of the strangeness quantum numbers. Most of them, like most hadrons with $S = 0$, decay by the strong interactions. However, conservation of quark numbers in strong and electromagnetic interactions means that if a particle is in the lightest state with a given non-zero set of B, Q and S values, it can only decay by weak interactions and so will be relatively long-lived. From this quark structure, Λ has $B = 1$, $Q = 0$ and $S = -1$. It is the lightest strange baryon. The lightest strange mesons are the kaons.

The production of strange particles in strong interactions is an example of *associated production.* In such processes, more than one strange particle is produced, giving strangeness conservation overall. A beautiful example of such an event is

$$\begin{array}{lccc} \pi^- + p & \to & K^0 + \Lambda \\ S: 0 \qquad 0 & = & 1 \quad -1 \end{array} \tag{1.43}$$

In the thirty years following the discovery of the pions and kaons, a great many hadrons were discovered. Until 1974 all could be accounted for as bound states of just the three quarks u, d and s originally proposed by Gell-Mann and Zweig. However, in that year a relatively heavy particle was discovered in two independent experiments - one at the Brookhaven National Laboratory (BNL) and the other at the Stanford Linear Accelerator Center (SLAC). The BNL group named this new particle J, while the SLAC group chose ψ. It is now known as J/ψ and its properties show that it is one of the lightest of a charm quark family. It is a bound state of a charmed quark and its antiparticle. That is

$$J/\psi(3097) = c\bar{c} \quad (C = 0)$$

Since $C = 0$, these states are often said to contain "**hidden charm**". Particles with "**naked charm**" ($C \neq 0$), were also discovered at SLAC shortly after the discovery of the J/ψ. Because charm is a quark number, like strangeness, it should be conserved in strong and electromagnetic interactions, and the lightest charmed particles should decay by weak interactions. This is indeed the case. For example, the lightest charmed mesons are the **D-mesons** with quark structures:

$$\begin{array}{rcll} D^+(1869) & = & c\bar{d} & (C=+1) \\ D^-(1869) & = & d\bar{c} & (C=-1) \end{array}$$

while the lightest charmed baryon is

$$\Lambda_c^+(2285) = udc \quad (C=+1)$$

These particles all have lifetimes of order $10^{-13}s$, which is in the expected range for weak decays. Charmed particles can be produced in strong and electromagnetic interactions by associated production reactions, just like strange particles. However, because the charmed particles have much shorter lifetimes than the strange particles K and Λ, they travel much shorter distances before decaying, and very good spatial resolution is needed to observe their tracks.

Historically, the discovery of strange particles caused great excitement because they clearly represented a new form of matter which was completely unexpected at the time. The discovery of charmed particles caused equally great excitement because their existence was expected, having been predicted from the newly formulated theory of electroweak interactions. Their discovery was a decisive event in confirming the essential correctness of this theory, which is a unified theory of both weak and electromagnetic interactions.

In its present form it requires that the number of leptons and quarks should be the same, implying that there should be six quarks to match the six known leptons. Evidence for the fifth quark - the bottom quark b with its associated quantum number beauty $\tilde{B}$ came from the discovery in 1977 of one of the lightest "bottomium" states

$$Y(9460) = b\bar{b} \quad (\tilde{B}=0)$$

which is a hidden beauty state called the **upsilon.** Subsequently the **B-mesons**

$$\begin{array}{rcll} B^+(5279) & = & u\bar{b}, & B^0(5279) = d\bar{b} \quad (\tilde{B}=+1) \\ B^-(5279) & = & b\bar{u}, & B^0(5279) = b\bar{d} \quad (\tilde{B}=-1) \end{array}$$

and the baryon

$$\Lambda_b^0(5461) = udb \quad \tilde{B}=-1$$

were also discovered, with "naked" beauty $\tilde{B} \neq 0$ and lifetimes of order $10^{-12}s$, consistent with weak decays. The top quark is too unstable to form observable hadrons and the evidence for its existence is obtained in quite a different way.

1.3.6 Top quark

By the 1977 there were five known quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} \\ b \end{pmatrix} \tag{1.44}$$

so that once again an extra quark - the **top quark** - was needed to restore the lepton-quark symmetry. By 1994, the mass of this quark had been predicted to be

$$m_t = 170 \pm 30 GeV/c^2 \tag{1.45}$$

by arguments based on small effects in the unified theory of electroweak interaction. The top quark was finally detected at Fermilab in 1995 with a mass

$$m_t = 178.1^{+10.4}_{-8.3} GeV/c^2 \tag{1.46}$$

compatible with the prediction of (1.45).

The properties of the top quark differ markedly from those of the other quarks because it is so much heavier. In particular, it is much heavier than the $W^\pm$ bosons. Hence, it can decay by the first-order weak interaction

$$t \to q + W^+ \quad (q = d, s, b) \tag{1.47}$$

as shown in Figure 1.9.

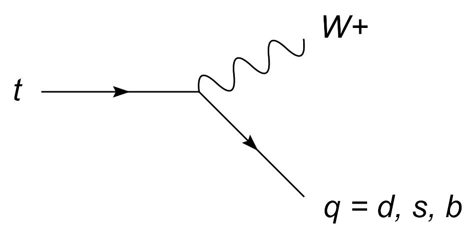


Figure 1.9: The mechanism for t quark decay. The decays which which lead to b quarks are overwhelmingly the most important.

After calculating the coupling constants of interaction (1.47), we find out that the only significant decay mode is

$$t \to b + W^+ \tag{1.48}$$

A crude dimensional estimate of the decay width $\Gamma \sim \alpha_W m_t \sim 1GeV$ ($\alpha_W = 4.2 \times 10^{-3}$) is enough to establish that the top quark is highly unstable. A full calculation for $m_t = 180GeV/c^2$ leads to the prediction $\Gamma = 1.7GeV$, with a corresponding lifetime

$$\tau = \Gamma^{-1} \approx 4 \times 10^{-25} s \tag{1.49}$$

This prediction is a body of top quark physics. By relativity, a hadron state of diameter $d = 1fm$ cannot be formed in at time less than $\tau_f \approx d/c = 10^{-22}s$.

The other five quarks $u,\ d,\ s,\ c$ and b have lifetimes of order $10^{-12}s$ or more and there is plenty of time for them to form hadrons which can be observed in the laboratory. In contrast, when top quarks are created they decay too rapidly to form observable hadrons. Instead they decay by (1.48) to give a b quark and a W-boson, which in turn decays predominantly to either light quarks

$$W^+ \to q_1 + \bar{q}_2 \quad (q_1\bar{q}_2 = u\bar{d}, u\bar{s}, c\bar{d}, c\bar{s}) \tag{1.50}$$

or leptons

$$W^+ \to l^+ + \nu_l \quad (l = e, \mu, \tau) \tag{1.51}$$

Furthermore, the quarks released in these decays are not seen directly, but "*fragment*" into **jets** of hadrons. This is shown in Figure 1.10 which shows the observable final states resulting from top quark decay.

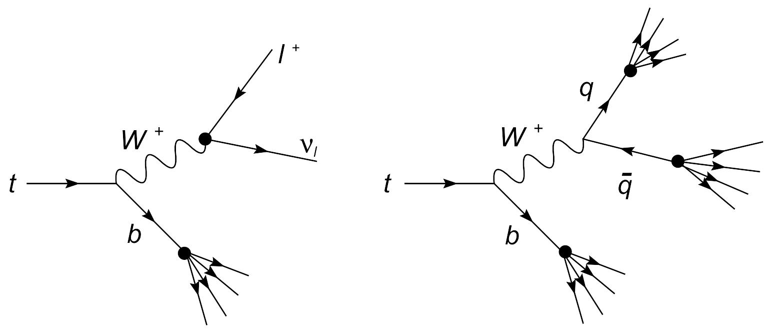


Figure 1.10: Production of hadron jets from the decay $t \to b + W^+$, where the W-boson decays to give hadrons or leptons.

1.3.7 Discovery of the top quark

Top quarks were first produced in pairs in the reaction

$$p + \bar{p} \to t + \bar{t} + X^0 \tag{1.52}$$

where X^0 is an arbitrary hadronic state allowed by the conservation laws. These pairs were identified by their subsequent decay product. The dominant decays of the t quark are shown in Figure 1.10, while the $\bar{t}$ quark decays by the corresponding antiparticle reactions. Clearly the final state resulting from the initial $t\bar{t}$ pair is very complicated and difficult to identify in the presence of backgrounds form other processes. In addition, very high energies are required if such pairs are to be produced at a reasonable rate in the reaction (1.52). The dominant mechanism for this is shown in Figure 1.11 and involves the quark-antiquark annihilations process

$$q + \bar{q} \to t + \bar{t} \tag{1.53}$$

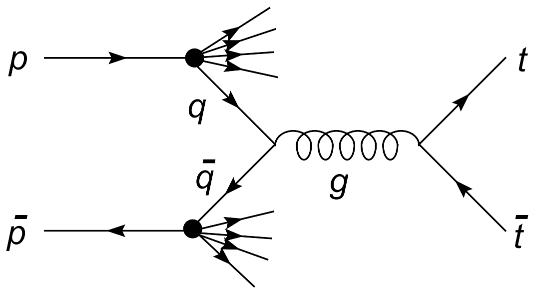


Figure 1.11: The dominant process for top quark production in proton - antiproton collisions at $1.8TeV$.

This can only occur if the total energy of the $q\bar{q}$ pair is at least $2m_t \approx 360GeV$, corresponding to the top quark and antiquark being produced at rest. Since each initial quark (or antiquark) carries only a fraction of the initial proton (or antiproton) energy, the energy of the $p\bar{p}$ system must be much higher if reasonable reaction rate is to be obtained.

These problems were first overcome by two experiments at Fermilab in 1995. In both cases, proton and antiproton colliding beams were brought together at the center of a very large and complex detector. the proton and antiproton beams each had an energy of $900GeV$, corresponding to a total center-of-mass energy of $1.8TeV$ overall. Both detectors could reconstruct very complicated multiparticle events, and both could detect and identify all long-lived particles except neutrinos. Here the description of its use to identify a particular class of events will be given. In these, top quarks decay by (1.48) to give

$$t + \bar{t} \rightarrow b + W^+ + \bar{b} + W^-. \tag{1.54}$$

One of the W-bosons then decays to give light quarks, while the other decays to give either an electron or a muon. The result is therefore either

$$t + \bar{t} \rightarrow l^+ + \nu_l + q + \bar{q} + b + \bar{b} \quad (l = e, \mu) \tag{1.55}$$

or

$$t + \bar{t} \rightarrow l^- + \bar{\nu}_l + q + \bar{q} + b + \bar{b} \quad (l = e, \mu) \tag{1.56}$$

where the quarks manifest themselves as hadron jets.

The measurement proceed like that: firstly, we identify an initial experimental signal corresponding to the desired events, then we consider what background processes could give rise to a similar signal and how they can be eliminated. Finally, the results can be presented.

a) <u>Initial event selection</u>

For each top quark event of the type (1.52) there are more than 10^9 events in which hadrons alone are produced. The extraction of a signal in the presence of this background is only possible since the top quarks are heavy and are produced with relatively low momenta. Because of this, their decay products are often emitted with large momenta at large angles to the initial beam direction. It is extremely rare for the hadrons produced in proton-antiproton collisions to be emitted with these characteristics. Hence the overwhelming majority of background events can be eliminated if events are selected which contain the combinations

$$\begin{array}{l} l^+ + \nu_l + N\ jets \quad (l = e, \nu) \\ l^- + \bar{\nu}_l + N\ jets \quad (l = e, \nu) \end{array} \tag{1.57}$$

where $N \geq 3$ and the leptons and jets are all required to have large momenta transverse to the incoming beams. Of course, neutrinos cannot be observed directly. However, since they are the only long-lived particles which are not detected, their presence can be revealed by summing the transverse momenta p_r of all the observed particles. If this sum is not zero within errors, as required by momentum conservation, the "*missing transverse momentum*" p_T is ascribed to neutrino.

Two further comments on the **initial trigger** (1.57) are required before we go on to see whether it can be produced in other ways. The first is that while (1.55) or (1.56) gives rise to four quarks, they will not always give rise to four distinct jets with high p_T. Sometimes one or more jets will be emitted close to the beam direction, where there are many hadrons from other sources. Sometimes two jet in the detector. The trigger specifies events in which at least three distinct jets emerge at high transverse momentum. The second point is that a high-momentum lepton could arise from the decay $Z^0 \rightarrow l^+l^-$ of a produced Z^0 boson, rather than a W-boson decay. In this case, the lepton would be part of an l^+l^- pair with invariant mass equal to the Z^0 mass. Such events are also removed from the sample.

b) Background events

So far we have identified a distinctive class of events which can arise from the production and decay of the top quarks. As in all experiments, it is necessary to consider whether such events could arise from other "*background*" processes. In the present case, the most important backgrounds arise when the subprocess (1.53) is replaced by a subprocess of the type

$$q + \bar{q} \rightarrow W^{\pm} + (N \geq 3) jets \tag{1.58}$$

Examples of such processes:

$$\begin{array}{rcl} q + \bar{q} & \rightarrow & W + q + \bar{q} + g + g \\ q + \bar{q} & \rightarrow & W + g + g + g \end{array} \tag{1.59}$$

are shown in Figure 1.12. If the W-boson decays to leptons, such processes can give rise to events which satisfy the trigger (1.57). Theoretical calculations and experimental observations both indicate that the ratio of events corresponding to this background to those for the "signal" of top quarks is about 4:1.

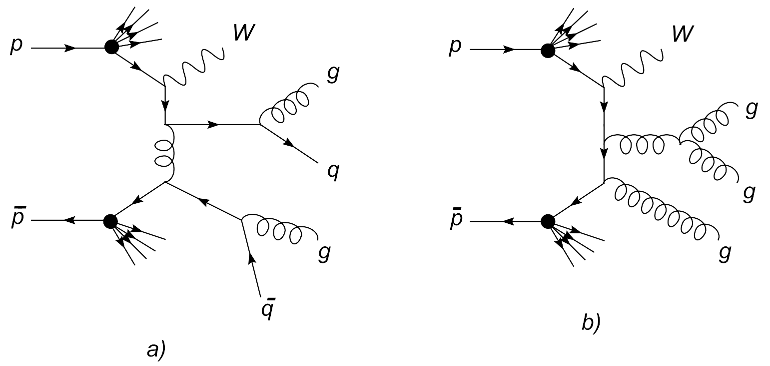


Figure 1.12: Reactions involving sub-processes (1.59) which contribute to the background for top quark production. The quarks and gluons are observed as jets.

c) b-jet tagging

Background events of the type (1.58) do not usually contain any jets associated with b quarks. This is illustrated by the examples in Figure 1.12, where the jets arise either from gluons or from quarks or antiquarks which originate from the proton or antiproton. In contrast, the top quark reaction (1.55) and (1.56) also invariably gives rise to b quarks. Hence the signal can be considerably enhanced relative to the background if "*b quark jets*" can be distinguished from jets arising from other quarks and gluons. This is called "**b-jet tagging**"

One of the most successful methods of b-jet tagging relies on the fact that b-jets nearly always contain a fast-moving hadron with non-zero beauty $\tilde{B} \neq 0$. Such particles are characterized by decays to many-particle final states, with lifetimes of about $10^{-12}s$. Hence b-jets typically contain multiprong decay veritces close to the production vertex. Other jets do not usually contain such vertices.

d) Final results

Since the observed dependence of the background on the various triggers is in good agreement with theoretical expectation, this is compelling evidence for the existence of the top quark. Furthermore, since four-jet events correspond to all the decay products of the top quarks being observed, it is possible to reconstruct the top quark mass from these events. The resulting mass distribution for four-jet events with a b-jet tag is shown in Figure 1.13. As can be seen, there is a clear peak, corresponding to a top quark mass

$$m_t = 176 \pm 8 \pm 10 GeV/c^2,$$

where the first error is statistical and the second is systematic. A similar result was obtained by the $D0$ experiment, also performed at Fermilab. The current best average value using all data is

$$m_t = 178.1^{+10.4}_{-8.3} GeV/c^2. \quad [3]$$

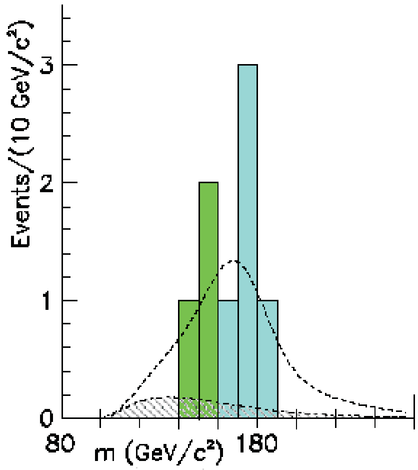


Figure 1.13: The reconstructed t quark mass distribution for the b-tagged events. The shape expected for background events is shown by shaded region.

To sum up, today's observation is focused primary on proton - antiproton process shown in Figure 1.14.

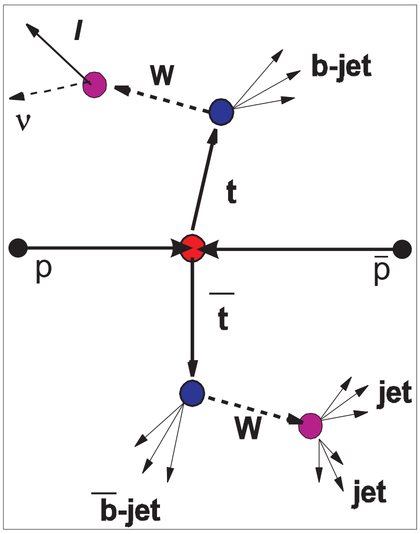


Figure 1.14: The most studied collision in present days.

1.4 Fundamental Interactions

1.4.1 Electromagnetic interaction

The electromagnetic interaction mediated by a photon γ has a long history of investigation and now it is known to be described by quantum electrodynamics (QED) which is the gauge theory having the Abelian $U(1)$ symmetry. QED is beautifully formulated in the framework of quantum field theory and is renormalizable, i.e. various divergences originated from the loop integrals in the higher orders of perturbation theory can be renormalized into physical masses and wave functions of particles. Because of smallness of the coupling constant $\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$, the perturbation works well for QED.

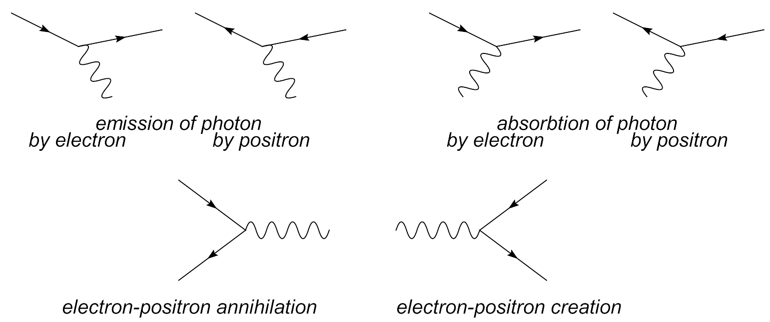
Action of interaction: EM interaction is selective interaction. It affects only particles with non-zero electric charge.

Range of interaction: infinite - there are elements with field intensity of $\frac{1}{r}$ which does not decrease even in infinity. These elements correspond to the electromagnetic waves.

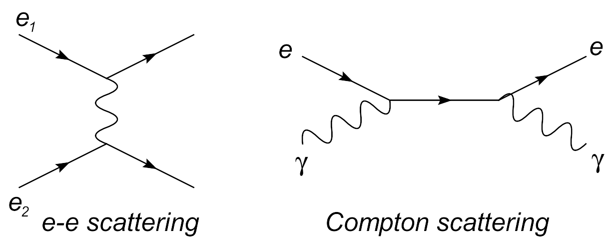
Symmetry of interaction: The equation of quantum field theory does not change under unitary transformation with one parameter - which can differ in every point of spacetime. Dependence on $t,\ x,\ y,\ z$ - local transformation $U(1)_Y$. Its straight consequence is the existence of electric charge.

Mediators: The symmetry of interaction is described by one free parameter (angle of rotation), which corresponds to one intermediate particle - the photon γ. Photon has zero mass. It is the consequence of uncertainty relations - if the interaction is supposed to has an infinite range, the mediator has to be massless.

Basic diagrams of electromagnetic interaction:



Examples of typical electromagnetic processes: The number of vertices correspond to the amplitude of probability and decrease with every extra vertex. This probability is proportional to the fine structure constant α. Only the free ends of Feynman diagrams are particles which can be detected. Lines, which begin and end in the vertex pitch corresponds to the virtual particles.



1.4.2 Weak interaction

The theory of weak interactions for weak processes originally formulated by Fermi, was developed in 1950´s and excellently described by the current-current interaction with V-A currents. It works well for low energy processes. Unfortunately, the theory is not renormalizable in spite of its small coupling constant. This is due to the fact that the Fermi coupling G_F has the dimension of $[mass]^{-2}$. Thus the Fermi interaction should be regarded as the effective model for weak processes working only in the low energy region. In the study of weak interaction physics in 1960's, many theoretical difficulties in the weak interaction appeared. A beautiful renormalizable theory was finally formulated, based on the unified picture of weak and electromagnetic interactions, in the framework of non-Abelian gauge theory with $SU(2)_L \times U(1)_Y$ symmetry (the subscript L means the fields participating in the interaction are left-handed and Y denotes the weak hypercharge), which is now called the electroweak standard model.

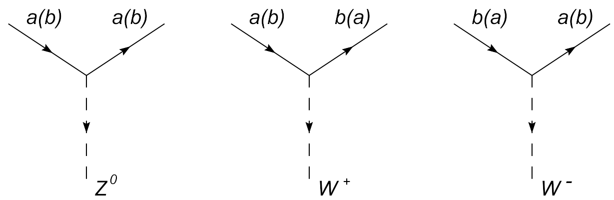
Action of interaction: Weak interaction is selective interaction. It affects only particles with non-zero weak charge - flavour. Flavour has leptons and quarks. Every generation has its own flavour - so that we have 6 flavours.

Range of interaction: finite - weak interaction has short range of order $10^{-17}m$. This means non-zero mass for mediate particles of interaction.

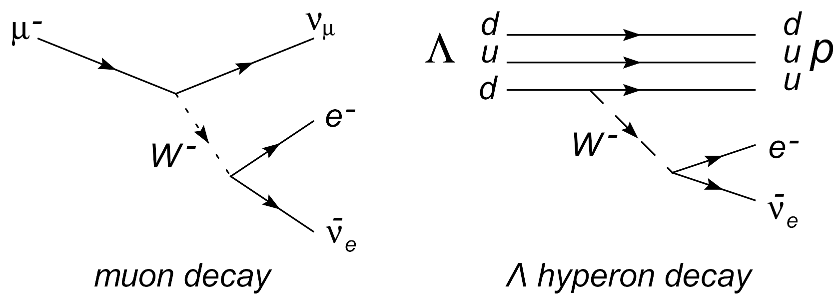
Symmetry of interaction: Weak interaction cannot distinguish particles with the same flavour and the symmetry is called $SU(2)$ - special unitary.

Mediators: The symmetry of interaction is described by the unitary complex matrices 2×2, which contain 4 elements. The ("*special*") $det = 1$ condition gives $4-1 = 3$ free parameters which correspond to 3 massive intermediate particles W^+, W^- a Z^0.

Basic diagrams of weak interaction: Basic diagrams are composed from lepton or quark channel and weak mediators. There are two types of diagram. First, similar to the EM interaction, Z^0 does not carry away any charge (*neutral current*). Secondly, W^+ and W^- carry charge away from the vertex (*charged current*).



Examples of typical weak processes: In contrast to the EM interaction, there are diagrams of two types. Firstly, Z^0 boson neutral current is very similar to the EM processes. Secondly, W^+ or W^- bosons carry away (or in) electric charge.



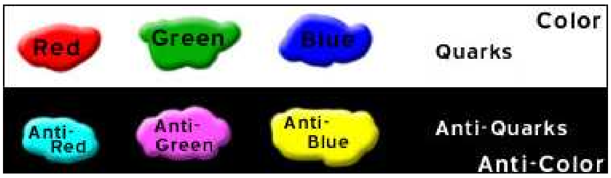
1.4.3 Strong interaction

The strong interaction is mediated by massless gluons which have color charge so they can couple to quarks. The field theory for the strong interaction is formulated in the non-Abelian gauge theory with $SU(3)_c$ color symmetry and is called quantum chromodynamics (QCD). The coupling constant of QCD has evident behaviour for a variation of momentum transfer square Q^2. The strong coupling constant $\alpha_s(Q^2) = \frac{{g_s}^2}{4\pi}$ "runs" as Q^2 varies. On one hand, $\alpha_s(Q^2)$ becomes small for large Q^2 region as realized in hard scattering such as deep inelastic scattering, where quarks and gluons behave as free particles, implied by the word "**asymptotic-free**", and in such regions the perturbation theory works well. On the other hand, for small Q^2 region as realized in the static state of bound quarks inside hadrons, $\alpha_s(Q^2)$ becomes large and in this hadrons (color singlet states). This is called the "**confinement**" phase. QCD must be the theory for describing the dynamics of quarks and gluons in all Q^2 regions from "asymptotic-free" to "confinement" phase.

Action of interaction: Strong interaction is selective interaction. It affects only particles with non-zero color charge.

What is color?

There are three color charges and three corresponding anticolor (complementary color) charges. Each quark has one of the three color charges and each antiquark has one of the three anticolor charges. Just as a mix of red, green, and blue light yields white light, in a baryon a combination of "red," "green," and "blue" color charges is color neutral, and in an antibaryon "antired," "antigreen," and "antiblue" is also color neutral. Mesons are color neutral because they carry combinations such as "red" and "antired."



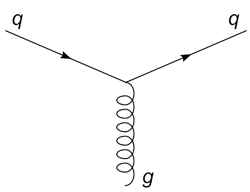
Because gluon emission and absorption always changes color and, in addition, color is a conserved quantity - gluons can be thought of as carrying a color and an anticolor charge.

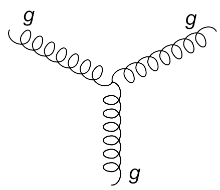
Range of interaction: finite - strong interaction has short range of order $10^{-15}m$.

Symmetry of interaction: $SU(3)_C$ - corresponds to 3 color charges.

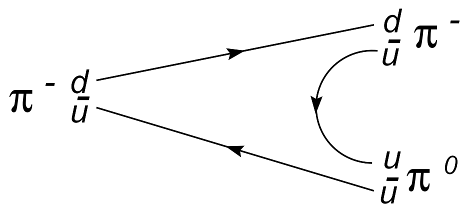
Mediators: The symmetry of interaction is described by the unitary complex matrices 3×3, which contain 9 elements. The "*special*" condition gives 1 equation. So there are $9 - 1 = 8$ free parameters which correspond to 8 intermediate particles - gluons. The gluons are supposed to be massless and their limited interacting range is probably caused by screening of the color field.

Basic diagrams of strong interaction:





Example of typical strong process:



meson decay, $q\bar{q}$ creation

1.4.4 Unification of interactions

Weak and electromagnetic interactions are formulated by the gauge theory with $SU(2)_L \times U(1)_Y$ symmetry and furthermore, the strong interactions are described by the gauge theory with color $SU(3)_c$ symmetry. Hence, one can naturally expect that all these interactions of elementary particles must be described by the gauge theory with some internal symmetry G, that is, the Lagrangian has to be invariant under the gauge transformations of G. The simplest example is to take the symmetry group G to be a direct product of each symmetry, $G = SU(3)_c \times SU(2)_L \times U(1)_Y$. The resultant theory is called **the Standard Model.** The important principle in the formulations is that

- the theory is the gauge theory
- it must be renormalizable and anomaly-free
- the symmetry breaking must occur spontaneously

However, the Standard Model has many problems to be solved and it is also believed that this is not the ultimate theory.

Chapter 2

Higgs Boson

2.1 Role of The Higgs Boson

The central challenge in particle physics today is to understand what differentiates electromagnetism from the weak interactions. The fundamental interactions derive from symmetries we have observed in Nature. One of the great recent achievements of modern physics is a quantum field theory in which weak and electromagnetic interactions arise from a common symmetry. This "electroweak theory" has been validated in detail, especially by experiments in the Large Electron Positron Collider (LEP) at CERN. Although the weak and electromagnetic interactions are linked through symmetry, their manifestations in the everyday world are very different. The influence of electromagnetism extends to infinite distances, while the influence of the weak interaction is confined to subnuclear dimensions, less than about $10^{-17}m$. That is to say, the photon, the force carrier of electromagnetism, is massless, whereas the W and Z particles that carry the weak forces are about a hundred times the mass of the proton.

What hides the symmetry between the weak and electromagnetic interactions? That is the question which is hoped to be answered through experiments at the Large Hadron Collider (LHC) at CERN. When the LHC is operational, it will enable to study collisions among quarks and qluons at energies approaching several TeV. A thorough exploration of the TeV energy scale will determine the mechanism by which the electroweak symmetry is hidden and teach us what makes the W and Z particles massive.

The simplest guess goes back to theoretical work by Peter Higgs and others in the 1960's. According to this picture, the giver of mass is a neutral particle with zero spin that is called the Higgs boson. In today's version of the electroweak theory, the W and Z particles and all the fundamental particles get their masses by interacting with the Higgs field, if you like the Higgs boson. But the Higgs boson remains hypothetical - it has not been observed, yet.

If the answer is the Higgs boson, it can be said enough about its properties to guide the search. Unfortunately, the electroweak theory does not predict the mass of the Higgs boson. However, consistency arguments require that it weigh less than $1TeV$. Experimental searches already carried out tell us that the Higgs must weigh more than about $120GeV$.

If the Higgs is relatively light, it may have been seen in electron-positron annihilations at LEP, produced in association with the Z. The Higgs boson would decay into a b quark and a $\bar{b}$ antiquark in these reactions, but no conclusive discovery has been made. In these days, experiments at Fermilab's Tevatron should be able to extend the search to higher masses, looking for Higgs plus W or Higgs plus Z in proton-antiproton collisions. If the Higgs mass exceeds about $130GeV$, our best hope is the LHC. Heavy Higgs bosons would be observed by their decay into WW or ZZ. Higher energy electron-positron colliders, or even muon colliders, could also play an important role.

The inability to predict the mass of the Higgs boson is one of the reasons many scientist believe that this picture cannot be the whole story. Therefore, a big effort is given to search for extensions to the electroweak theory that make it more coherent and more predictive. Two approaches seem promising. Both of them imply a rich harvest of new particles and new phenomena at the energies we are just beginning to explore at Fermilab and, in future, CERN. One is a supersymmetric generalization of the electroweak theory that associates new particles with all the known quarks and leptons and force particles. Supersymmetry entails several Higgs bosons. In the other approach, called dynamical symmetry breaking, the Higgs boson is not an elementary particle, but a composite.

Over the next few years, the riddle is supposed to be solved. One of the main goal in today's interest is a search for Higgs particle so we can expect big excitement every day LHC will be operating and acquiring data.

2.2 Need for Scalar Boson

The Weinberg, Salam and Glashow's $SU(2) \times U(1)$ gauge model of weak and electromagnetic interactions is a beautiful theory, many times confirmed. However, there are some divergencies that need to be cancelled, which in turn is necessary for renormalizability. In this section, we will illustrate on an example that a scalar boson is necessary in GWS model. In addition, connection between the scalar boson and particle masses will be uncovered.

Let's take WW scattering process. As high-energy divergences need to be canceled, one must think over all possible processes in WW scattering. They are shown in Figure 2.1. All high-energy divergencies are canceled if we sum all the diagrams form this figure. Only quadratically divergent contribution ($s = E^2$)remains (see (2.1)).

$$\mathbf{M}_{WW}^{(\gamma)} + \mathbf{M}_{WW}^{(Z)} + \mathbf{M}_{WW}^{(direct)} = -g^2 \frac{s}{4m_W^2} + O(1) \tag{2.1}$$

[The explicit expressions can be found in [5]] Since the coupling factor occurring in this expression is definitely non-zero, there is obviously no way how the diver-

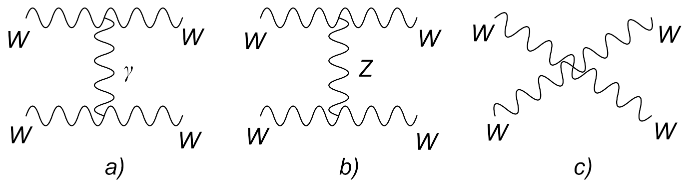


Figure 2.1: Diagrams for the process $WW \to WW$, including a) the photon, b) the Z boson exchange and the direct coupling of four W bosons.

gent term in (2.1) could be eliminated without introducing a new particle and a corresponding new interaction. The crucial observation is that the quadratic divergence in (2.1) can be cancelled in a most natural way by means of an additional diagram involving the exchange of a scalar boson. An interaction of a pair of the WW with a single neutral scalar field σ has an unique form if it is required to be of a renormalizable type (i.e. have dimension not greater than four). The σ-exchange diagrams of the WW scattering are shown in Figure 2.2. From this picture we get

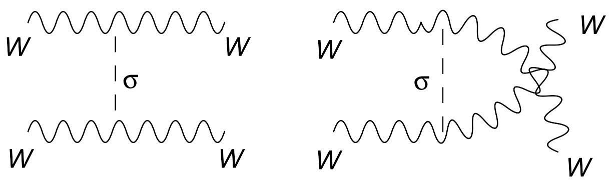


Figure 2.2: Neutral scalar exchange graphs for the WW scattering.

$$\mathbf{M}^{(\sigma)}_{WW} = g^2_{WW\sigma}\frac{s}{4m^4_W} + O(1) \qquad (2.2)$$

and it is obvious that the divergent terms in (2.1) and (2.2) cancel each other if and only if

$$g_{WW\sigma} = gm_W \qquad (2.3)$$

After all, the extra interaction of W bosons with a neutral scalar field σ does provide a remedy for the residual divergence in (2.1). At the same time, the result (2.3) shows remarkable connection of such a "compensating" coupling with the W boson Mass.

So, the theory try to generate masses through appropriate interactions involving scalar fields. This scalar field got name according to Petr Higgs (*1929), who first published this idea in 1964.

2.3 Spontaneous Symmetry Breaking

The simple model associated with **spontaneous symmetry breaking**, originally invented by J.Goldstone, is so-called **Goldstone model**. Starting with a classical theory, the model is described by the Lagrangian density of the type

$$\mathfrak{L} = \partial_\mu \varphi \partial^\mu \varphi^* - V(\varphi) \tag{2.4}$$

where φ is a complex field

$$\varphi = \frac{\sqrt{2}}{2}(\varphi_1 + i\varphi_2)$$

and $V(\varphi)$ the potential energy

$$V(\varphi) = -\mu^2 \varphi\varphi^* + \lambda(\varphi\varphi^*)^2 \tag{2.5}$$

where μ is a real parameter with dimension of mass and λ is a (dimensionless) coupling constant which we assume to be positive in order that total field energy is bounded from below. The essential feature of the considered Lagrangian is the "wrong sign" of the mass term in (2.5). Leaving temporarily the $\lambda\varphi^4$ term, the result is Klein-Gordon equation $(\Box - \mu^2)\varphi = 0$ with reversed sign of mass squared. The Lagrangian is invariant under the global $U(1)$ transformation describing rotations in the complex plane. It should be noted that φ is a function of the spacetime coordinate x which is suppressed to simplify the notation.

Requiring that the vacuum, the lowest energy state, is invariant under Lorentz transformations and translations implies that $\varphi(x)$ is a constant in this vacuum state. Two different possibilities exist for the vacuum state depending on the parameter $-\mu^2$. If $-\mu^2$ is positive the situation is quite normal with the minimum potential energy when $\varphi = 0$. If instead $-\mu^2$ is negative, the minimum energy no longer corresponds to a unique value of φ. Let's consider the latter case and considering a constant φ, the minimum of the potential V can be found easily. The V in fact depends only on one real variable ϱ defined as $\varrho = \varphi\varphi^*$ so that instead of (2.5) one can write

$$V(\varrho) = -\mu^2\varrho^2 + \lambda\varrho^4. \tag{2.6}$$

The first derivate $V'(\varrho)$ vanishes for $\varrho = 0$ and for $\varrho^2 = \mu^2/2\lambda$. The value $\varrho = 0$ corresponds to a local maximum, while for $\varrho = \pm\mu/\sqrt{2\lambda}$ there is an absolute minimum of the V. In terms of the original variable φ it means that the minimum of the energy density corresponds to a one-parametric set of constant values

$$\varphi_0 = \frac{v}{\sqrt{2}} e^{i\alpha} \tag{2.7}$$

where α is an arbitrary number (for example $0 \leq \alpha < 2\pi$) and v denotes

$$v = \frac{\mu}{\sqrt{\lambda}} \tag{2.8}$$

so-called "**vacuum**". This relation fixes a notation that has become standard for electroweak theories involving Higgs mechanism.

The potential (2.5) is schematically drawn in Figure 2.3. In fact, the full picture would consist of a surface formed by rotating this curve around the ordinate axis (Figure 2.4).

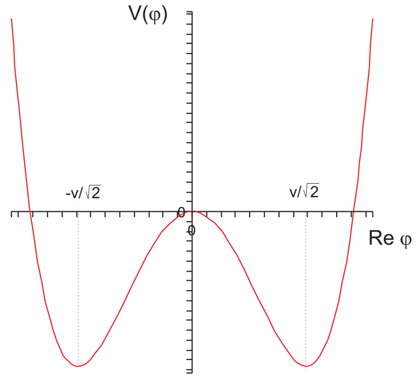


Figure 2.3: A 2D visualization of the Goldstone potential given by (2.5).

In other words, the φ_0 values that minimize the energy density lie on a circle in the complex plane with radius $v/\sqrt{2}$ and the energy minimum is thus infinitely (continuosly) degenerate. Such a finding, namely the observation that the ground state of the considered system is described by a non-zero constant field, leads to the following simple idea: instead of the φ, one should perhaps use its deviation from the "vacuum value" (2.8) as a true dynamical variable. It also seems to be more promising to study small oscillations around a stable ground state with $|\varphi| = v/\sqrt{2}$, rather than take as a reference point the value $\varphi = 0$ corresponding to an unstable state. This idea can be implemented mathematically in a rather elegant way if the original Lagrangian (2.4) is first rewritten in terms of radial and angular field variables defined by

$$\varphi(x) = \varrho(x) exp\left(\; i\frac{\pi(x)}{v} \; \right) \tag{2.9}$$

(the factor 1/v in the exponent ensures the right dimension of mass for the angular field $\pi(x)$). Using (2.9) in (2.4) one gets

$$\mathfrak{L} = \partial_\mu \varrho \partial^\mu \varrho + \frac{1}{v^2} \varrho^2 \partial_\mu \pi \partial^\mu \pi - V(\varrho). \tag{2.10}$$

For further purpose, it is useful to rewrite the potential (2.6) in a slightly different way using (2.8)

$$V(\varrho) = \lambda(\varrho^2 - \frac{v^2}{2})^2 - \frac{1}{4}\lambda v^4 \tag{2.11}$$

The additive constant appearing in the last line can be dropped without changing anything essential - only the energy density thus becomes automatically non-negative. So, now the Lagrangian (2.10) can be replaced by the equivalent form

$$\mathfrak{L} = \partial_\mu \varrho \partial^\mu \varrho + \frac{1}{v^2}\varrho^2 \partial_\mu \pi \partial^\mu \pi - \lambda(\varrho^2 - \frac{v^2}{2})^2 \tag{2.12}$$

Now, the mentioned shift (oscillation) of the field variable will be made. The ϱ may be rewritten as

$$\varrho = \frac{1}{\sqrt{2}}(\sigma + v), \tag{2.13}$$

using (2.13) in (2.12)

$$\mathfrak{L} = \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma + \frac{1}{2}\partial_\mu \pi \partial^\mu \pi - \frac{1}{4}\lambda(\sigma^2 + 2v\sigma)^2 + \frac{1}{2v^2}\sigma^2 \partial_\mu \pi \partial^\mu \pi + \frac{1}{v}\sigma \partial_\mu \pi \partial^\mu \pi \tag{2.14}$$

that is

$$\mathfrak{L} = \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma + \frac{1}{2}\partial_\mu \pi \partial^\mu \pi - \lambda v^2 \sigma^2 + interactions \tag{2.15}$$

where all terms higher than quadratic have been generically denoted as "interactions". The important point is that the σ field now has a mass term with the "right sign", while the π came out to be massless. In particular, the σ mass value that can be read off from (2.15) is $\frac{1}{2}m_\sigma^2 = \lambda v^2$, i.e.(using (2.8)) $m_\sigma^2 = 2\mu^2$. In fact, the appearance of a mass term with correct sign should not be surprising. Our "shift" of the radial field variable actually means that we perform Taylor expansion around a local minimum of the potential, where its second derivative is of course positive. However, this second derivative determines the coefficient of the term quadratic in the relevant field - which is the mass term in the Lagrangian.

In the above exercise we have seen that the model (2.4) describes in fact two real scalar fields σ and π where

$$m_\sigma = \mu\sqrt{2}, \quad m_\pi = 0. \tag{2.16}$$

A most remarkable feature of the considered model is the appearance of the massless field π - which implies the existence of a massless bosonic excitation (**Goldstone boson**). A familiar example of an approximate Goldstone boson in particle physics is the pion. From many experimental facts in low-energy phenomenology, the pions $\pi^\pm \pi^0$ are explained to be massless. Their masses as observed in the real world are assumed to be due to an additional explicit symmetry breaking.

From the above situation it can be also seen how the spontaneous symmetry breaking of the U(1) symmetry caused by the degenerate energy minimum of the Lagrangian (2.4) creates a perturbation theory with a massive scalar boson(why not call it **Higgs boson** and the σ field **Higgs field**). Then, P.Higgs made trick to make Goldstone bosons unphysical and one gets a mass term for the vector field.

2.4 Higgs Mechanism

The Higgs mechanism try to give explanation of how the elementary particles acquire mass. As was said in previous sections, these masses arise from interactions with the Higgs field.

The Higgs field is a quantum field which differ from all other quantum fields in three crucial ways.

The first difference is somewhat technical. All fields have spin, an intrinsic quantity of angular momentum that is carried by each of their particles. The Higgs boson, the particle of the Higgs field, has spin 0. Having 0-spin enables the Higgs field to appear in the Lagrangian in different ways than the other particles do.

The second unique property of the Higgs field explains how and why it has nonzero strength throughout the universe. Any system, including a universe, try to tumble into its lowest energy state, like a ball bouncing down from a hill to the bottom of a valley. The lowest energy state is the one in which the fields have zero value. But for the Higgs field, the energy is lower if the field is not zero but instead has a constant nonzero value.

In terms of the valley metaphor, for ordinary fields the valley floor is at the location of zero field; for the Higgs, the valley has a stand-alone hill at its center (at zero field - see Figure 2.4) and the lowest point of the valley forms a circle around the hill. The universe, like a ball, comes to rest somewhere on this circular trench, which corresponds to a nonzero value of the field. That is lowest energy state and the universe is permeated throughout by a nonzero Higgs field.

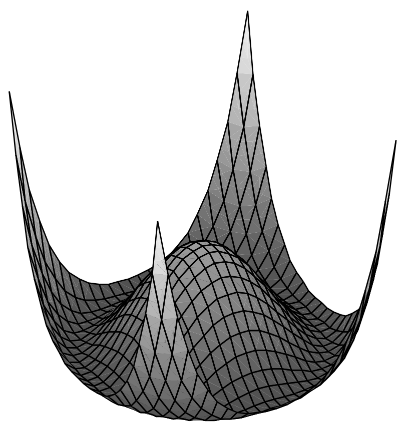


Figure 2.4: Picture of the stand-alone hill, i.e. a graph of the spontaneous symmetry breaking function

The final distinguishing characteristic of the Higgs field is the form of its interactions with other particles. Particles that interact with the Higgs field behave as if they have mass, proportional to the strength of the field times the strength of the interaction. The masses arise from the terms in the Lagrangian that have the particles interacting with the Higgs field.

Theorists have several reasons for expecting the standard model picture of the Higgs interaction to be correct. First, without the Higgs mechanism, the W and Z bosons that mediate the weak force would be massless, just like the photon (which they are related to), and the weak interaction would be as strong as the electromagnetic one. Theory holds that the Higgs mechanism confers mass to the W and Z in a very special manner. Predictions of that approach (such as the ratio of the W and Z masses) have been confirmed experimentally.

Second, essentially all other aspects of the Standard Model have been well tested, and with such a detailed, interlocking theory it is difficult to change one part (such as the Higgs) without affecting the rest. For example, the analysis of precision measurements of W and Z boson properties led to the accurate prediction of the top quark mass before the top quark had been directly produced. Changing the Higgs mechanism would spoil that and other successful predictions.

Our understanding of all this is not yet complete, however, and we are not sure how many kinds of Higgs fields are there. Although the Standard Model requires only one Higgs field to generate all the elementary particle masses, physicists know that the Standard Model may be substituted by a more complete theory. One of the most promising extensions of the Standard Model known as Supersymmetric Standard Models (SSMs). In these models, each Standard Model particle has a so-called superpartner (as yet undetected) with closely related properties. With the Supersymmetric Standard Model, at least two different kinds of Higgs fields are needed. Interactions with those two fields give mass to the Standard Model particles. They also give some (but not all) mass to the superpartners. The two Higgs fields give rise to five species of Higgs boson: three that are electrically neutral and two that are charged. The masses of neutrinos could arise in rather different way or from yet a third kind of Higgs field. Finally, the SSM can explain why the energy "valley" for the universe has the shape needed by the Higgs mechanism. In the basic Standard Model the shape of the valley has to be put in as a postulate, but in the SSM that shape can be derived mathematically.

On the other hand, the Standard Model Higgs mechanism works very well for giving mass to all the Standard Model particles, W and Z bosons, as well as quarks and leptons; the alternative proposals usually do not.

Chapter 3

Searching Higgs

3.1 Introduction

The existence of the Higgs boson is the most important prediction of the standard model which has not been verified by experiment and searches for it are a high priority at most accelerators, both present and planned. A problem in designing suitable experiments is that the Higgs boson mass is not predicted by the theory. However, its coupling to other particles are predicted by the theory and are essential proportional to the mass of the particle to which it couples. The Higgs boson therefore couples very weakly to light particles like neutrinos, electrons, muons and u, d and s quarks. On the other hand it couples more strongly to heavy particles like $W^{\pm}$ and Z^0 bosons and t quarks. Hence, attempts to produce Higgs bosons are made more difficult by the need to first produce the very heavy particle to which they couple.

The failure to observe Higgs bosons in present experiments is due to limits on their mass. The best results came from LEP at CERN, which reached energy up to $110GeV$. The reaction used in LEP was

$$e^+ + e^- \rightarrow H^0 + Z^0.$$

What follows next is to present the huge potential of LHC in searching Higgs and summary of FNAL experiments results concerning Higgs boson search.

3.2 LHC Search

The Large Hadron Collider (LHC) in Geneva expected to start operations in summer, will play an important role in Higgs discovery by colliding two 7 TeV poton beams every 25ns. Two optimized detectors, ATLAS (A Toroidal LHC ApparatuS) and CMS (Compcat Muon Solenoid) are expected to cover all the Higgs mass range from GeV region to 1 TeV, larger than the allowed range expected by the theoretical and experimental constraints of previous experiment. The mode of production of the Higgs boson is dominated by the gluons fusion and vector boson fusion, seconded by associated production with a $W^{\pm}$, Z or heavy quarks. Feynman diagrams for this processes are shown in Figure 3.1 and the production cross section graph in Figure 3.2.

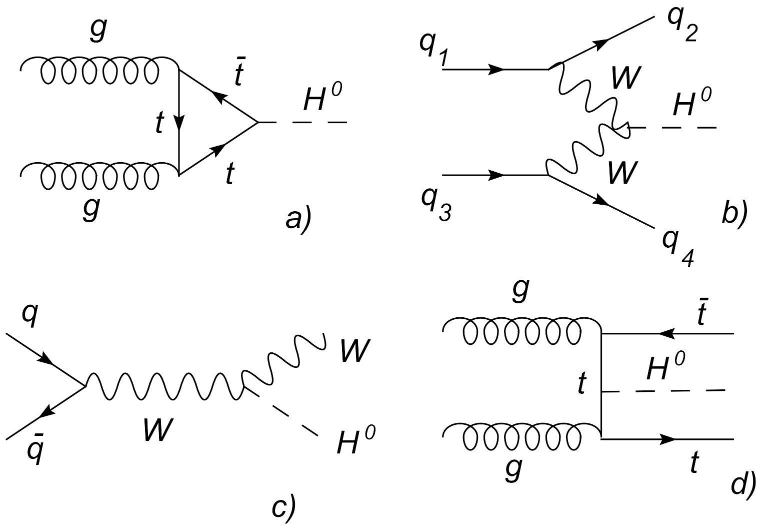


Figure 3.1: The most important processes for Higgs production at hadron colliders. a) gluon fusion, b) vector boson fusion, c) associative production with W, d) associative production with a top pair.

The detection of Higgs particle(s) is made via its decay products and, accordingly to its mass, there are 3 energy regions in which Higgs may be found. Each region has its own dominanting or interesting decay channels, which are shown in Figure 3.3. The regions of Higgs masses are

- low mass range
- intermediate mass range
- high mass range

3.2.1 Low Mass Range ($\mathbf{m_Z < m_H < 2m_Z}$)

To find a Higgs particle below the threshold for the $H \rightarrow ZZ$ decay and above the limit set by the searches at $LEP2$ will be difficult. The obvious way to detect a Higgs would be in the dominant $H \rightarrow b\bar{b}$ channel but with the b-quarks fragmenting into jets this channel will be overwhelmed by the QCD background. Also the $H \rightarrow b\bar{b}$ decay lacks any trigger as it neither has high jet energies nor isolated leptons in the final state. A more favourable situation can be obtained by either looking at associative production or at one of the rarer decays.

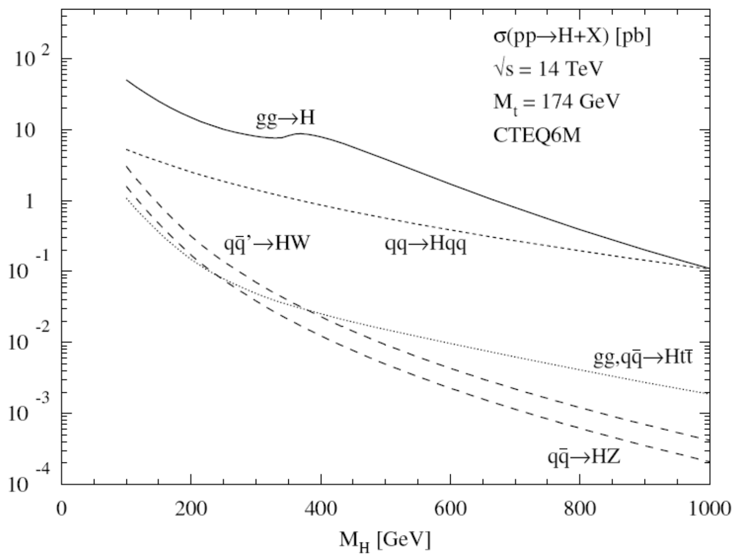


Figure 3.2: Production cross sections for Higgs boson at LHC as a function of its mass.

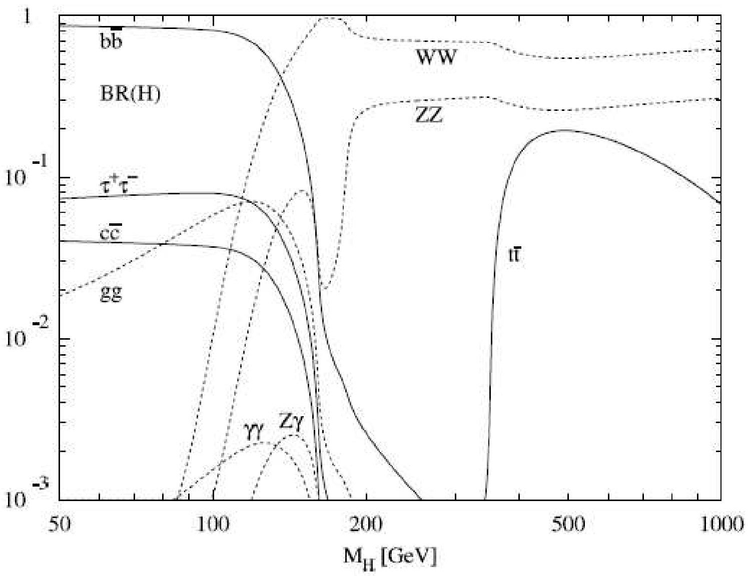


Figure 3.3: Branching rations for the main channels of Higgs boson at LHC as a function of its mass.

With the Higgs produced together with either a top quark pair or a vector boson ($t\bar{t}H$, WH, ZH), the problem of getting a trigger for the Higgs events are solved by requiring a high energy lepton from one of the top quarks or the vector boson decay $t \rightarrow W(\rightarrow l\mu)b$ and $t \rightarrow W(\rightarrow q\bar{q})b$. The next handle for the decay is to identify the jets with b-quarks. The method called b-tagging, described in top quark section, is based either on the long lifetime of the b-quarks which causes secondary vertices or on the high amount of leptons in B meson decays. While the HW mode will in general have two b-quarks in the final state, the $Ht\bar{t}$ will have four because $t \rightarrow b$. But the $H \rightarrow b\bar{b}$ decay gives further problems in the reconstruction.

The other way of identifying a Higgs in this region is to select an exotic decay as the $H \rightarrow \gamma\gamma$ decay (Figure 3.3). The trigger is two isolated electromagnetic clusters. While the channel suffers from a low branching ratio around 10^{-3}, the backgrounds are also much lower than in the case of the $H \rightarrow b\bar{b}$ decay due to the clear signature of two isolated photons in the final state. The main backgrounds are from direct photon production and jets faking photons. This motivates the choice for LAr (ATLAS) and $PbWO_4$ (CMS) electromagnetic calorimeters.

3.2.2 Intermediate Mass Range ($\mathbf{2m_Z < m_H < 650GeV}$)

If a standard model Higgs is having a mass above twice the Z mass the discovery will be easy through the decay channel $H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$. This is called the golden channel for Higgs decays. Both lepton pairs will have an on-shell Z mass making it possible to reduce many types of backgrounds. The main irreducible background is direct ZZ production, but a requirement for at least one of the Z bosons to have a transverse momentum above half the Higgs mass will strongly suppress this background. The upper mass limit for detecting the Higgs in this decay channel is given by the reduced production rate and the increased width of the Higgs.

3.2.3 High Mass Range ($\mathbf{m_H > 650GeV}$)

With the fixed collision energy of the LHC the production cross section of a Higgs particle falls with an increasing Higgs mass. The rate in a selective decay channel like the four lepton channel is thus no longer high enough for the highest Higgs masses. With the decays to vector bosons totally dominating, the only possible detection channels left, are with at least one of the vector bosons decaying to neutrinos or jets. The decay channel $H \rightarrow W^+W^- \rightarrow l\nu jj$, where j denotes a jet from a quark in the W decay, has a branching ratio of just below 30% giving it a rate some 50 times higher than the four lepton channel from $H \rightarrow ZZ$ decays. However, the background from direct jW and $t\bar{t}$ production are large and can only be reduced requiring forward jets in the event. The decay channel $H \rightarrow ZZ \rightarrow l^+l^-\nu\bar{\nu}$ which has a six times larger branching ratio than the four lepton channel could also be interesting.

So we have seen that there are many ways to discover Higgs boson at LHC. In Figure 3.4 are presented statistical significances for the Standard Model Higgs boson. Combining these results for all channels should allow a 7σ discovery over the whole mass spectrum with $30fb^{-1}$.

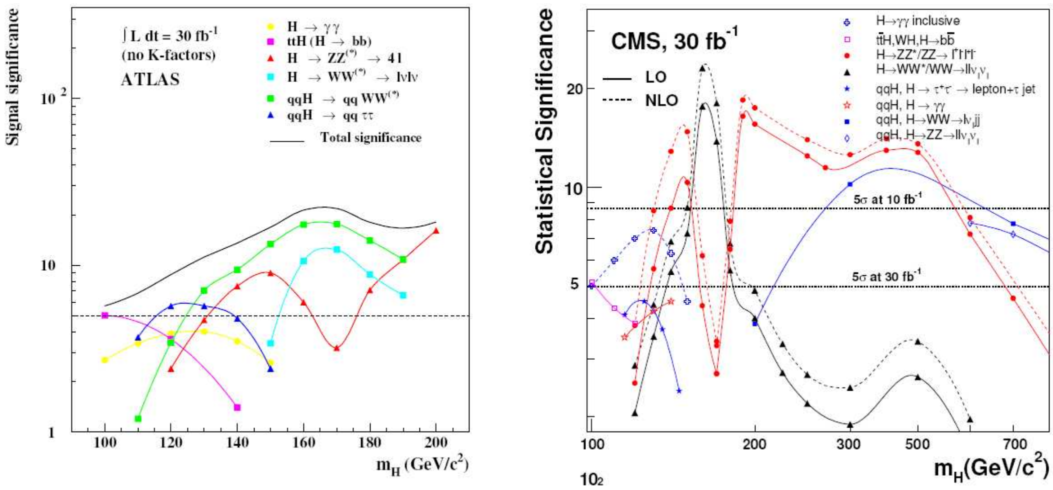


Figure 3.4: Potential of discovery (significances) at the LHC for the ATLAS (left panel) and the CMS (right panel) experiments.

3.3 FNAL Search

Tevatron is a circular synchrotron at the Fermi National Accelerator Laboratory in Batavia, Illinois and is currently the highest energy operational particle collider in the world. The Tevatron accelerates protons and antiprotons in a $6.3km$ ring to energies of up to CMS $2TeV$. The Tevatron was completed in 1983 and is currently the only accelerator capable of producing a **low mass Higgs boson.** Detailed discussion on low mass Higgs is given in previous section.

The Higgs boson can be produced via several mechanisms at the Tevatron. The process with the largest cross section is $gg \rightarrow H$ (the same at LHC, Figure 3.2) However, in the low mass region ($100 < mH < 140GeV/c2$), where the Higgs decays primarily to a $b\bar{b}$ pair (Figure 3.3), this channel is overwhelmed with background from generic QCD processes. The more promising modes at the Tevatron are the production of the Higgs boson in association with either a W or Z boson. The decays $W \rightarrow l\bar{\nu}$ and $Z \rightarrow \nu\bar{\nu}$, l^+l^- provide an important signature for extracting the signal from background. In addition, the two b-quark jets tagging give a second important handle. Despite these two unique features, substantial backgrounds still exist. The primary sources of background are $t\bar{t}, W/Zb\bar{b}, WZ, ZZ$, single top quark production and QCD processes.

The experiments CDF and $D\emptyset$ collaborations agreed to form working groups for a study of the light Higgs. In order to produce the result in a timely manner, the two working groups divided the effort. The $D\emptyset$ working group focused on the $\nu\bar{\nu}b\bar{b}$ final state, primarily produced via $p\bar{p} \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$, while the CDF working group focused on the $l\bar{\nu}b\bar{b}$ final state, primarily produced via $p\bar{p} \rightarrow WH \rightarrow l\bar{\nu}b\bar{b}$.

In 1998 physicists from the CDF and $D\emptyset$ collaborations and the Fermilab Theoretical Physics Department organized a workshop to study the potential for discovering the Higgs boson in Run II of the Fermilab Tevatron. Their findings are summarized in Figure 3.5.

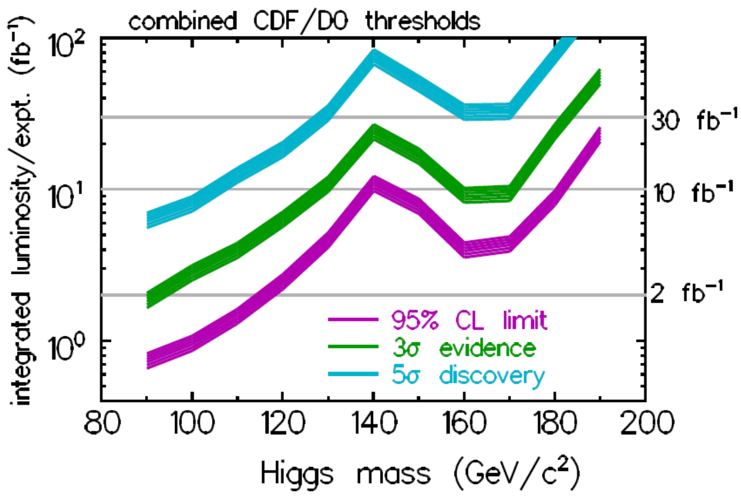


Figure 3.5: Summary of the findings of the SUSY-Higgs Working Group study. The vertical axis is the required integrated luminostiy per experiment for three different levels of Higgs search sensitivity: 95% CL exlusion (confidence level), 3σ evidence and 5σ discovery.

Current limits for Higgs boson are set by LEP2 (CERN) experiment and are to be $m_H > 114GeV$ at 95% CL. But also using theoretical precision electroweak fit we get (winter 2005) [17]

$$m_H = 126^{+73}_{-48}GeV$$

and

$$m_H < 280GeV \ at \ 95\%CL.$$

Acquired LEP2 results along with theoretical prediction are shown in Figure 3.6. The preliminary results from Run IIA at $D\emptyset$ experiment were published in **march 2006** and the next few lines will summarize those results.

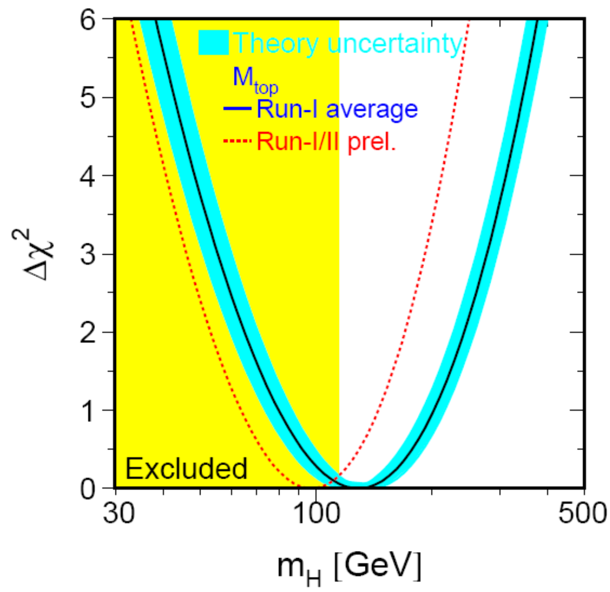


Figure 3.6: Theoretical uncertainty of the Higgs mass, LEP2 results included.

3.3.1 $l\bar{\nu}b\bar{b}$ Analysis

This is one of the cleanest search channels at the Tevatron collider for Higgs boson masses of $m_H < 145GeV$. More clearly - Higgs production associated with a vector boson: $p\bar{p} \rightarrow WH$, where the vector boson undergoes a leptonic (e, μ) decay $W \rightarrow l\nu$ and the Higgs boson decays as $H \rightarrow b\bar{b}$ pair. Since the expected production cross section for a Higgs boson associated with a W, when combined with leptonic branching ratio of the W, is significantly larger than that for associated production with a Z boson, the search for the Higgs boson in the final state of $e\nu b\bar{b}$ (2005 results) and $\mu\nu b\bar{b}$ (2006 results) is more promising and corresponds to a total integrated luminosity of $378pb^{-1}$,

To sum up, WH production (together with $Wb\bar{b}$) at a center of mass energy of $\sqrt{s} = 1.96TeV$ was searched. Considered final states contained one high p_T lepton, missing transverse energy E_T from W decay and one or two $b\ jets$. Detailed comparisons of data and background estimated from the standard model showed no excess above expectation. The search for the Higgs boson in the $b\bar{b}$ invariant mass shows no excess of events above the background in the mass range of $105 < m_H < 145GeV$. The results for both leptons provides upper limits on WH production cross section ranging from $2.4pb$ to $2.9pb$ for m_H between $105GeV$ and $145GeV$. Expected limits with correlations from other $D\emptyset$ cooperatives are shown in Figure 3.7.

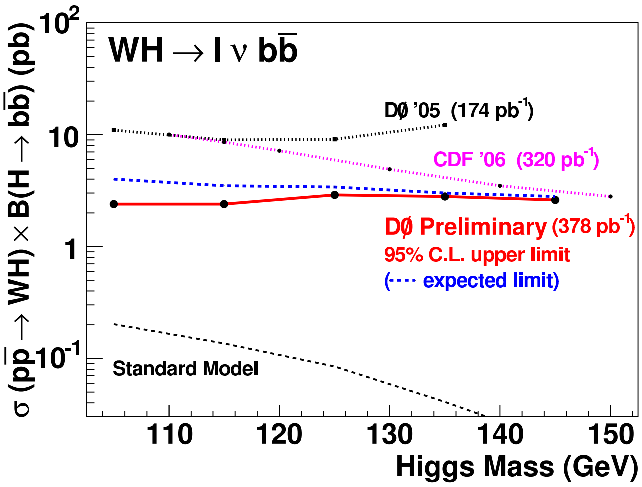


Figure 3.7: 95% confidence level upper limit on cross section times branching ratio $B(H \to b\bar{b})$, and corresponding expected limit, obtained by this analysis with an average integrated luminosity of $378pb^{-1}$, on WH production(W boson decaying into a lepton + neutrino and Higgs into $b\bar{b}$ versus Higgs mass. Also shown are the $D\emptyset$ analysis using the electron channel only ($174pb^{-1}$), published in 2005, the CDF published analysis (e, μ channels, $320pb^{-1}$, 2006) and the Standard Model expectation.

3.3.2 $\nu\bar{\nu}b\bar{b}$ Analysis

The $\nu\bar{\nu}b\bar{b}$ channel searches for the presence of a large missing transverse energy E_T from Z decay and two identified b-quarks jets. This channel selects events from the process $p\bar{p} \to ZH$, with $Z \to \nu\bar{\nu}$, and $H \to b\bar{b}$. There is also a substantial efficiency for selecting events from the process $p\bar{p} \to WH$, with $W \to l\nu$ and $H \to b\bar{b}$, where the lepton is not identified in the event.

The analysis, based on an integrated luminosity of $261pb^{-1}$, starts with a sample of multijet events with large imbalance in transverse momentum. Then, events with two b-tagged jets are selected and searched for a peak in their invariant mass distribution.

Finally, 95% CL upper limits were set between 2.5 to 3.4 pb on the cross section for ZH production multiplied by the branching ratio for $H \to b\bar{b}$. These results were (and are!) used to add and correct new limits for the $D\emptyset$ combined Higgs boson searches.

It is believed, that Higgs boson searches at Tevatron have a huge importance in low mass region, because acquiring data from LHC will take some time and at last, but not at least, using LHC for searching low mass Higgs has many problems which must be yet solved.

Chapter 4

Pythia Simulations

The Pythia program was developed to generate high-energy-physics events, i.e. sets of outgoing particles produced in the interactions between two incoming particles. The objective is to provide as accurate as possible representation of event properties in a wide range of reactions, within and beyond the Standard Model. The goal of the "event generator" is not to give the exact answer to all the problems connected with current physics, but instead, its purpose is just to "factorizing" the full problem into a number of components, where each of them can be handled reasonably accurately.

In the actual generation procedure, most steps therefore involve the branching of one object into two, or at least into a very small number, with the daughters free to branch in their turn. As the name indicates, the output of an event generator should be in the form of "events", with the same average behaviour and the same fluctuations as real data. In the data, fluctuations arise from the quantum mechanics of the underlying theory. In generators, Monte Carlo techniques are used to select all relevant variables according to the desired probability distributions, and thereby ensure (quasi-)randomness in the final events. An event generator can be used in many different ways. The five main applications are probably the following:

- To give physicists a feeling for the kind of events one may expect/hope to find, and at what rates.
- As a help in the planning of a new detector, so that detector performance is optimized, within other constraints, for the study of interesting physics scenarios.
- As a tool for devising the analysis strategies that should be used on real data, so that signal-to-background conditions are optimized. An example is given in Figure 4.1.
- As a method for estimating detector acceptance corrections that have to be applied to raw data, in order to extract the "true" physics signal.

- As a convenient framework within which to interpret the observed phenomena in terms of a more fundamental underlying theory (usually the Standard Model).

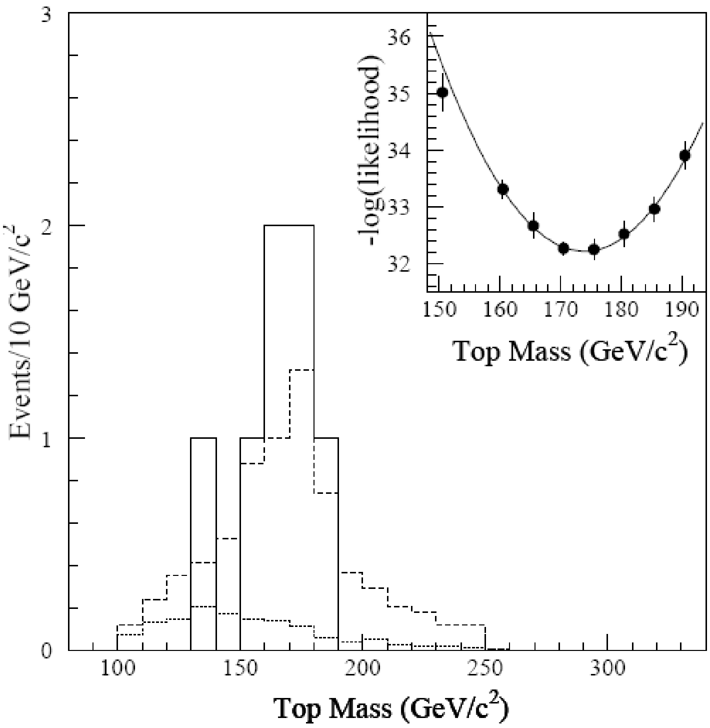


Figure 4.1: Top discovery event with background correlation using pythia (the lowest smooth curve is background, the highest peak is a measurement and the "Gauss" is correlated result).

4.1 Role of the event generator

So now, we can put a following question: Where does a generator fit into the overall analysis chain of an experiment? Look at the Figure 4.2 and at the following few lines.

In "real life", the machine produces interactions. These events are observed by detectors, and the interesting ones are written to tape by the data acquisition system. Afterward the events may be reconstructed, i.e. the electronics signals (from wire chambers, calorimeters, and all the rest) may be translated into a deduced setup of charged tracks or neutral energy depositions with full knowl-

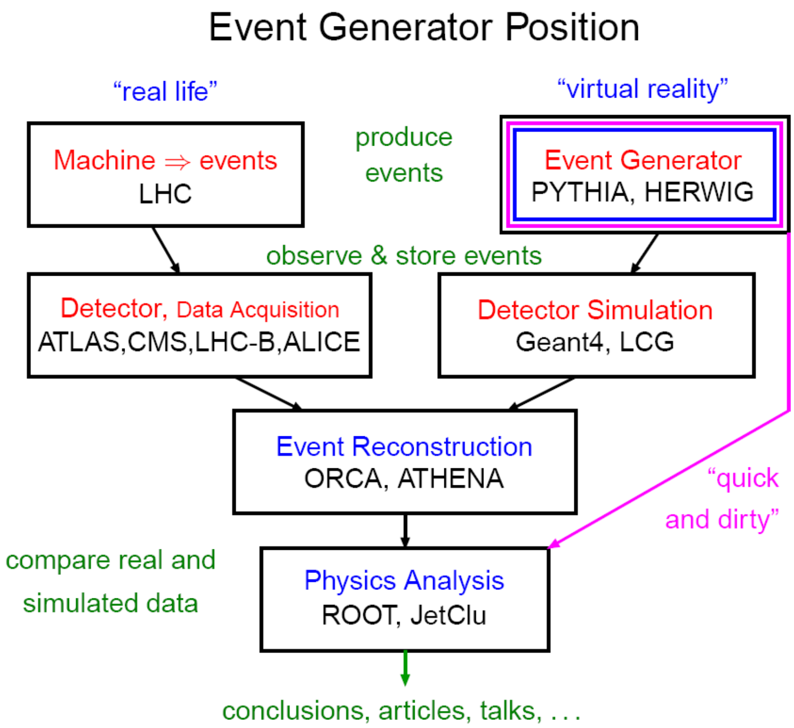


Figure 4.2: Position of the event generator in the chain of an experiment.

edge of momenta and particle species. Based on this cleaned-up information, one may proceed with the physics analysis.

In the Monte Carlo "virtual reality" the role of the machine is taken by the event generators. The behaviour of the detectors — how particles produced by the event generator traverse the detector, spiral in magnetic fields, shower in calorimeters, or sneak out through cracks, etc. — is processed in simulators of detectors - such as GEANT. Ideally, the output of this simulation has exactly the same format as the real data recorded by the detector, and can therefore be put through the same event reconstruction and physics analysis chain, except that here we know what the "right answer" should be, and so can see how well we are doing. Since the full chain of detector simulation and event reconstruction is very timeconsuming, it is useful to do just "quick and dirty" studies in which these steps are skipped entirely, or at least replaced by very simplified procedures which only take into account the geometric acceptance of the detector and other trivial effects.

So what is the main purpose of the event generator? As the experiments are moving into higher and higher energies, there is a huge amount of particles and analytical tools are not able to describe the whole complexity of the event.

So, sooner or later, every experimentalist is in need of an outline of what is happening in the experiment and the event generators are the best tools for this task.

4.2 Pythia event at work

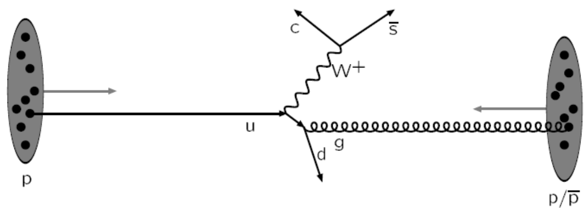
For the description of a typical high-energy event, an event generator should contain a simulation of several physics aspects. If we try to follow the evolution of an event in some semblance of a time order, one may arrange these aspects as follows:

1. Initially two beam particles are coming in towards each other. Normally each particle is characterized by a set of parton distributions, which defines the partonic substructure in terms of flavour composition and energy sharing.

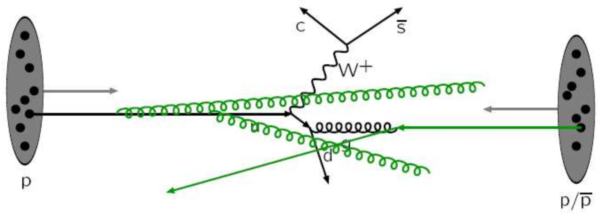
In Pythia, as a program input the incoming hadrons with their energies can be set. It is also possible to define the type of the parton interaction - i.e. take only qq interactions etc.

2. One incoming parton from each of the two showers enters the hard process, where then a number of outgoing partons are produced, usually two. It is the nature of this process that determines the main characteristics of the event.

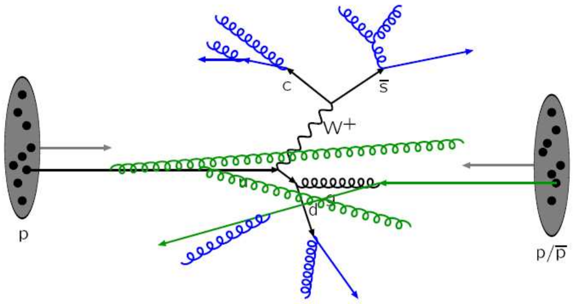
The hard process may produce a set of short-lived resonances, like the $Z_0/W^{\pm}$ gauge bosons, whose decay to normal partons, has to be considered in close association with the hard process itself.



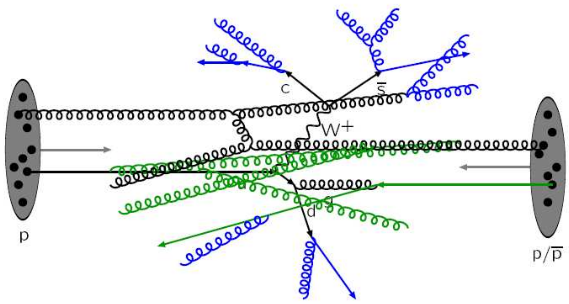
3. During this process an initial-state radiation is emitted from incoming partons (green curves).



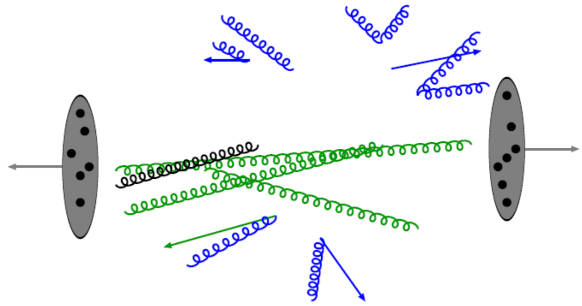
4. The outgoing partons may branch, just like the incoming did, to build up final-state radiation - showers (blue curves).



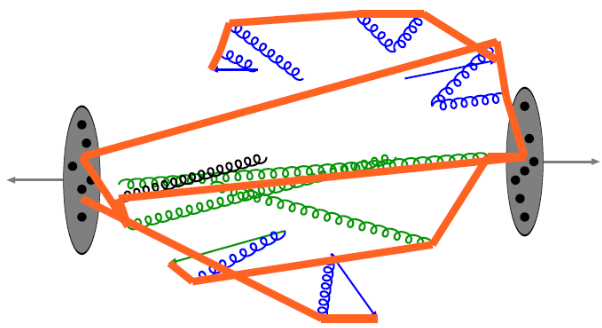
5. In addition to the hard process considered above, further semihard interactions may occur between the other partons of two incoming hadrons, so called multiple parton-parton interaction (black additional curves).



6. When a shower initiator is taken out of a beam particle, a beam remnant is left behind. This remnant may have an internal structure and a colour charge.

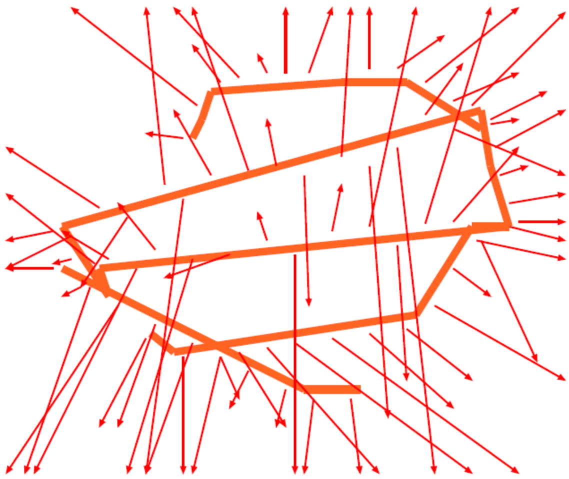


7. The QCD confinement mechanism ensures that the outgoing quarks and gluons are not observable, but there is a string colour confinement.



8. The strings fragment to produce primary hadrons and subsequently many of the produced hadrons are unstable and decay further.

Finally, during these processes, all ordinary decays, namely leptonic, are also included adding even more complexity to the event generator. Furthermore, PYTHIA goes even beyond the Standard Model and can cover technicolor, new gauge bosons and, of course, many types of Higgs bosons from different theories.



All the particles covered by PYTHIA are given numerical codes according to their substructure. This codes are the same as used by The Particle Data Group (out of some exception). The basic building blocks of matter, quarks and leptons, with their codes are shown in Table 4.2. The gauge bosons are

KF code	Name	KF code	Name
1	d	11	e^-
2	u	12	ν_e
3	s	13	μ^-
4	c	14	ν_μ
5	b	15	τ^-
6	t	16	ν_τ
7	b'	17	τ'
8	t'	18	ν'_τ

Table 4.1: Quark an lepton codes, including the fourth generation as part of the scenarios for exotic physics.

enumerated in a similar way. All these codes can be found in [22]. Codes of mesons and baryons are consequently composed from these basic element codes. For example baryons:

$$KF_{baryon} = 1000i + 100j + 10k + 2s + 1,$$

where i, j and k are quarks with $i \geq j \geq k$ and total spin s. See:

$$n = 2112,\ p = 2212,\ \Lambda^0 = 3122,\ \Delta^- = 1114$$

4.3 Future

PYTHIA is one of the most popular and complex event generator used in hig-energy particle physics. Nevertheless, the program is still being developed - nowadays, the current version of PYTHIA is 6.X, but a radically new version of the program is required, because the original one is written in Fortran and the new age requires C++ adoption (version 8). In our simulations, we included PYTHIA libraries right into root program. Then, it was very easy to substract and process data from there.

Chapter 5

No Higgs at All

Since Higgs mechanism explains how particles acquire mass in very elegant way, there are some theories which do not count with Higgs boson at all. Some of them, such as superstring theory, destroy the standard model completely and try to explain all phenomena in rather different way. On the other hand, some theories stay close to the standard model and, for example, explain mass by modification of the electroweak model.

5.1 Hierarchy problem

In theoretical physics, a hierarchy problem occurs when the fundamental parameters (couplings or masses) of some Lagrangian are vastly different (usually larger) than the parameters measured by experiment. This can happen because measured parameters are related to the fundamental parameters by a prescription known as renormalization. Typically the renormalized parameters are closely related to the fundamental parameters, but in some cases, it appears that there has been a delicate cancellation between the fundamental quantity and the quantum corrections to it.

Studying the renormalization in hierarchy problems is difficult, because such quantum corrections are usually power-law divergent which means that the shortest-distance physics are most important. Because we do not know the precise details of the shortest-distance theory of physics (quantum gravity), we cannot even address how this delicate cancellation between two large terms occurs.

The question is why the Higgs boson is so much lighter than the Planck mass

$$m_P = \sqrt{\frac{\hbar c}{G}} \approx 1.2209 \times 10^{19} GeV/c^2$$

$$G \ldots gravitational\ constant$$

although one would expect that the large (quadratically divergent) quantum contributions to the square of the Higgs boson mass would inevitably make the mass huge, comparable to the scale at which new physics appears.

Given this hierarchy problem with the Higgs boson mass, it is expected that new physics should make an appearance at energy scales not much higher than the scale of energy required to produce the Higgs boson, and thereby provide an explanation for its small mass.

The most popular theory — but not the only proposed theory — to solve the hierarchy problem is supersymmetry. This explains how a tiny Higgs mass can be protected from quantum corrections. Supersymmetry removes the power-law divergences of the radiative corrections to the Higgs mass, however, there is no understanding of why the Higgs mass is so small.

5.1.1 Note to the Supersymmetry

Supersymmetry (SUSY) is a generalization of the space-time symmetries of quantum field theory that transforms fermions into bosons and bosons into fermions. In supersymmetric theories, all existing particles are accompanied by partners having opposite spin-statistics. It also provides a framework for the unification of particle physics and gravity, which is governed by the Planck scale (defined to be the energy scale where the gravitational interactions of elementary particles become comparable to the gauge interactions - see above). It is an appealing concept, for which there is currently no direct experimental evidence.

Now let's go back to the hierarchy problem - due to the Higgs field scalar nature, the mass it acquires through interactions are as large as the largest mass scale in the theory squared! Thus, in any unified model, the Higgs mass tends to be enormous. Such a large Higgs mass cannot be, however, since it would ruin the successful perturbation expansion used in all standard model calculations. Thus in order to get the required low Higgs mass, the bare mass must be fine-tuned to dozens of significant places in order to precisely cancel the very large interaction terms and not disrupt the hierarchy. At each order of the perturbation expansion (loop-expansion), the procedure must be repeated. However, if supersymmetric partners are included, this fine-tuning is not needed. The contribution of each supersymmetric partner cancels off the contribution of each ordinary particle. Schematically drawn in Figure 5.1.

This works only if the supersymmetric partners have masses below the TeV range. Thus, stabilization of the gauge hierarchy is accomplished automatically, as long as supersymmetric particles exist and have masses in the range 100-1000 GeV. The enormous effort going into searches for supersymmetric particles at CERN and Fermilab is largely motivated by this argument.

Another piece of puzzle which can be explained via SUSY theory is the problem of *"Grand unification of interaction"*. The strength of the strong, weak, and electromagnetic interactions is set by the value of their coupling constants, and these "constants" change as the energy of the interactions increase. For example, the electromagnetic coupling constant $\alpha = 1/137$, has a value near $1/128$

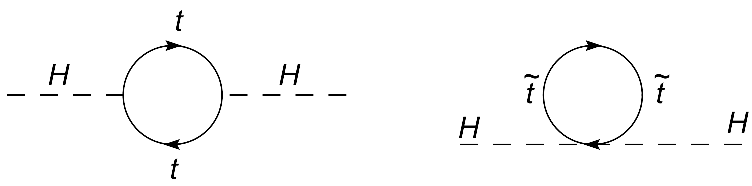


Figure 5.1: Cancellation of the Higgs boson quadratic mass renormalization between fermionic top quark loop and scalar stop squark tadpole Feynman diagrams in a supersymmetric extension of the Standard Model.

when electrons were collided at the LEP machine at CERN. Several decades ago it was noticed that the three coupling constants would meet together at a universal value when the energy of interactions reached about $10^{15} GeV$. This would allow a Grand Unification of the strong, weak, and electromagnetic interactions. In the past few years, the values of the three coupling constants have been measured much more accurately, and it is now clear that, in fact, they cannot unify at any scale unless many new particles are added to the theory. The unification of interactions in the view of coupling constants are shown in Figure 5.2.

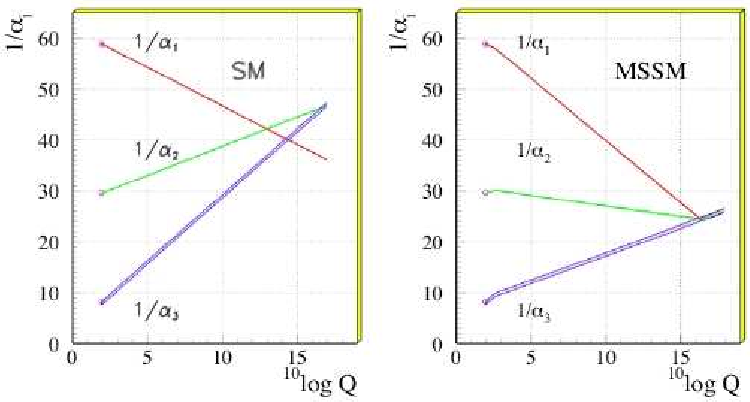


Figure 5.2: Left: current course of coupling constants; Right: Supersymmetric correlation of these constants which then meet at one point.

To sum up, SUSY is promising in explaining some painful parts of the Standard Model, namely the **Minimal Supersymmetric Standard Model** (MSSM) - the minimal extension to the Standard Model that realizes supersymmetry and is in a close agreement with the classical Standard Model. Concerning this work, a single Higgsinos (the fermionic superpartner of the Higgs boson) would lead to a gauge anomaly and would cause the theory to be inconsistent. However if a pairs of Higgsinos are added, there is no gauge anomaly. The simplest theory is one with a single pair of Higgsinos and therefore a pair of scalar

Higgs doublets. In addition to this previous argument, a pair of Higgs doublets (called the up-type Higgs and the down-type Higgs) is desired in order to have renormalizable Yukawa couplings between the Higgs and all the Standard Model fermions. This means 4 Higgs boson totally in MSSM.

5.2 Theories without Higgs particle

Electroweak no Higgs model is EW model which avoids using Higgs mechanism. It indroduces two sets of gauge bosons so as to keep the masses of gauge bosons $W^{\pm}$ and Z non-zero without Higgs mechanism. The theory assumes five kinds of massless gauge bosons and some of them, for example Z_2, have similar interaction properties to those of γ photon including its mass, so it is hard to distinguish between γ photon and Z_2 boson in experiment. If experimental physics find that γ photon takes part in weak interactions, that means that there exists Z_2 boson mixed in γ photon. Charged massless gauge bosons $W_2^{\pm}$ might be regarded as charged photon or other light charged particles (such as an electron is supposed to simultaneously create an invisible neutrino). The standard model with these new gauge bosons can coexists with Higgs particle, but if these massless bosons were found by experiment, Higgs particle is no longer needed in theory.

The top quark condensate theory is an alternative to the Standard Model without a scalar Higgs field, or alternatively, the Higgs field is a composite field. The top and antitop quark forms a bound state described by a composite scalar field. This composite field forms a condensate, leading to a fermion condensate which spontaneously breaks the electroweak and hypercharge symmetry into electromagnetism. This model predicts that the electroweak scale matches the top quark mass, which it does.

The nice thing about this theory is that there is no problem of stabilizing the Higgs mass squared from quadratically divergent radiative corrections (Hierarchy problem discussed above), and thus, no need for supersymmetry.

Technicolour models are theories beyond the Standard Model (often based on unified theory of fundamental interaction) which do not have a scalar Higgs field. Instead, they have a larger number of fermion fields than the Standard Model and involve a larger gauge group. This larger gauge group is spontaneously broken down to the Standard Model group as fermion condensates form.

The idea of technicolor is to build a model in which the sort of dynamics we see in quantum chromodynamics (QCD) can be used to explain the masses of the W and Z bosons. In QCD, there are quarks that feel both the weak interaction and the strong interaction. The strong interaction binds them together in condensates which spontaneously break electroweak symmetry.

In fact, QCD itself gives masses to the W and Z bosons, but these masses are tiny compared to the observed masses. Technicolor uses a QCD-like theory at a higher energy scale to give the observed masses to the W and Z bosons. Unfortunately the simplest models are already experimentally ruled out by precision tests of the electroweak interactions. There is currently no fully satisfactory model of technicolor, but an effort to make it consistent still remains as the Higgs field was not verified yet.

(Super)string theory is a model of fundamental physics whose building blocks are one-dimensional extended objects (strings) rather than the zero-dimensional points (particles). For this reason, string theories are able to avoid problems associated with the presence of pointlike particles in a physical theory.

The basic idea is that the fundamental constituents of reality are strings of energy of the Planck length (about $10^{-35}m$) which vibrate at resonant specific frequencies (that represents different particles). Another key claim of the theory is that no measurable differences can be detected between strings that wrap around dimensions smaller than themselves and those that move along larger dimensions (i.e., physical processes in a dimension of size R match those in a dimension of size 1/R). Singularities are avoided because the observed consequences of "big crunches" never reach zero size. The avoiding singularity phenomena is shown in Figure 5.3.

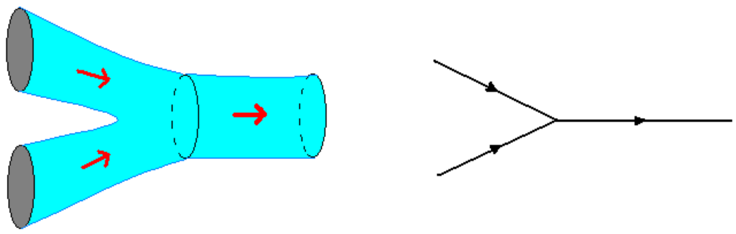


Figure 5.3: An example of the annihilation of two closed strings into a single closed string (left). The wolrldsheet is a smooth surface, so there are no infinities in the way thtat point particle quantum field theories are. The analogous Feynman diagram in a point particle Standard Model is shown as well (right).

One interesting feature of string theory is that it predicts the number of dimensions which the universe should possess. Nothing in Maxwell's theory of electromagnetism or Einstein's theory of relativity makes this kind of prediction. These theories require physicists to insert the number of dimensions "by hand". The only problem is that when the calculation of dimension is done, the universe's dimensionality is not four as one may expect (three axes of space and one of time), but 26. More precisely, bosonic string theories are 26-dimensional, while superstring and M-theories (explained later) turn out to involve 10 or 11 dimensions.

The superstring theory is an attempt to explain all particles and fundamental forces in one theory by modeling them as vibrations of tiny supersymmetric strings. It is advanced "bosonic string theory". The biggest potential in superstring is givent to the explanation of gravity, the fourth force of nature, which is not precisely described by the Standard Model. Firstly, there were five superstring theories in 10 dimensions, but in 1990s it was found that these five superstring theories are just different limits of a single underlying theory in 11-dimension space: **M-theory.** If we add 11-D Supergravity, our picture of present supersymmetry is completed - see Figure 5.4.

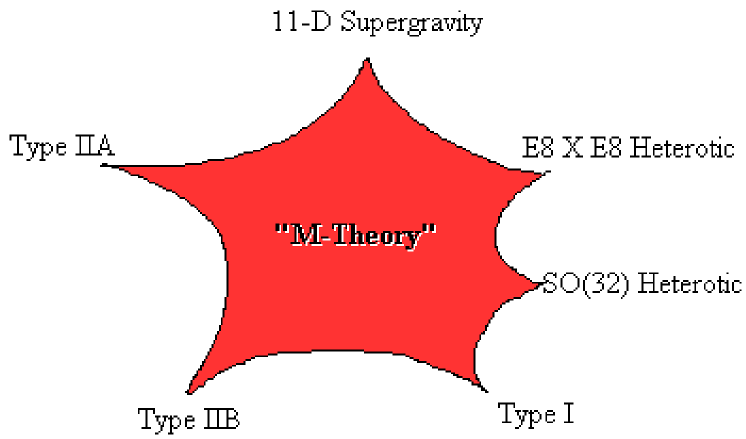


Figure 5.4: The M-Theory put all previous string theories together into final 11-dimensional model.

Nowadays, "string theory" usually refers to the supersymmetric variant while the earlier is given its full name, "bosonic string theory".

String theory as a whole has not yet made falsifiable predictions that would allow it to be experimentally tested, though various special corners of the theory are accessible to planned observations and experiments.

Summary and Outlook

Nowadays the Standard Model is the most detailed theory, which requires 12 matter particles and 3 force carriers. The last SM matter particle, the top quark, was discovered in 1995, at Fermilab. The next steps for confirmation of the Standard Model is the (non)discovery of Higgs boson and adding the fourth force, gravity, into the SM.

Firstly, the gravity is very far from current understanding and with the power of interaction of $\sim 10^{-39}$ can be neglected - for this time. But not forever and there is a big "vacuum" of theories which tries to interpret this force (beside the superstring theory, which includes gravity in its basics).

Secondly, the Higgs boson. Its search had begun on the LEP accelerator at CERN. LEPII set the bottom threshold for the Higgs boson mass to

$$m_H > 114GeV \; at \; 95\% \; CL.$$

This threshold is constantly being shifted towards higher values at Tevatron (FNAL). This experiment also shows, that Higgs mass should be below 280GeV. Thus, it will be very interesting to watch the first result from LHC accelerator, because there are many more or less significant channels in which Higgs boson may be produced in that mass range. The most promising, because of its clear signal, is the $H \to \gamma\gamma$ channel. However, the LHC start is planned to summer 2007, so the Tevatron can yet give us big surprise, but the scientists are there almost at the end of the possible energy scale set by the Tevatron construction. Thus, the challenge remains.

Before LHC starts, the whole effort for Higgs boson search is just to the simulate relevant processes and evaluate "old" data. For modeling Higgs production, the best way is to use PYTHIA event generator.

Finally, what if Peter Higgs and the others were wrong and the manner in which particles acquire mass is totaly different from the elegant Higgs mechanism? Do not be sad, there are many theories, both extending the Standard Model (MSSM) or excluding it totally (superstrings).

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