Neutrino Oscillations and Charged Higgs Bosons – Experimental Projects for Physics beyond the Standard Model

CHRISTIAN HANSEN
Abstract

This thesis is based on work done in two different experimental projects.

The first project, the Tau RICH, is a previously proposed τ-neutrino appearance experiment for the CERN neutrino beam at the Gran Sasso laboratory in Italy. The proposed experimental concept is based on the use of focusing RICH detectors with liquid radiator (C,F₃). Simulations made with a Geant4 code show that in the proposed experimental set-up, Cherenkov light from delta electrons will constitute a severe background that in practice would render the experiment unfeasible.

The second project, ATLAS, is a general purpose detector at the CERN 14 TeV proton-proton collider LHC which will start operation in 2007. To make the reconstruction and selection of the events in ATLAS more accurate, complete and up-to-date information on the interaction of the produced particles with the detector is needed. A service program code, the Material Integration Service (MIS), has been developed which makes use of the detector descriptions already available in a Geant4 code and which uses a novel algorithm, based on line integrals evaluated within small volume elements that build up the detector. This code is demonstrated to constitute a practically useful tool of satisfactory performance and accuracy.

The charged Higgs boson production in the gluon-bottom quark mode, gb → tH⁺, followed by charged Higgs decays into a chargino and a neutralino, is studied for a specific choice of values for the Minimal Supersymmetric Standard Model (MSSM) parameters. It is shown, using a Monte Carlo code to simulate the ATLAS detector and the assumed MSSM physics model, that for an integrated luminosity of 300 fb⁻¹, in the intermediate region 4 < tanβ < 10 where H⁺ decays to SM particles cannot be used for H⁺ discovery, charged Higgs decays to non-SM particles can be used for Higgs discovery at the 5 σ significance level.

Keywords: CERN, LHC, ATLAS, charged, Higgs, SUSY, MSSM, oscillating, neutrino, RICH, CNGS, HPD

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List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Simulation of a RICH detector for tau neutrino appearance
T. Ekelöf, R. Forty, C. Hansen

II Limitations in the use of RICH counters to detect tau-neutrino appearance
T. Ekelöf, R. Forty, C. Hansen, C. Joram, J. Seguinot

III Material Integration Service for the ATLAS Inner Detector
S. Armstrong, C. Hansen, R. Sandström

IV Discovery potential for a charged Higgs boson decaying in the chargino-neutralino channel of the ATLAS detector at the LHC
C. Hansen, N. Gollub, K. Assamagan, T. Ekelöf

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Work done for this thesis has also been presented in the following publications

• A RICH detector for tau neutrino appearance
  T. Ekelöf, C. Hansen and R. Forty

• Aerogel as Cherenkov radiator for RICH detectors
  Bellunato, T. and others

• Performance of aerogel as Cherenkov radiator
  Bellunato, T. and others
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1 Introduction

The Standard Model of Elementary Particles has been enormously successful as a theory that describes with high accuracy all measurements and observations in High Energy Physics made till now. However, when extrapolating the Standard Model to higher energies than those available at today's particle colliders one encounters instabilities in the theory which are difficult to control (“the hierarchy problem”) and which make it improbable that the Standard Model will give a correct description at higher energies. Several extensions of the Standard Model exist which give more stable predictions at these higher energies. The main objective of the present thesis is to study the sensitivity of two different experiments to test specific predictions of the theories beyond the Standard Model. The first chapter starts by summarizing the basic characteristics of the SM in section 2.1 and presenting some specific physics beyond the SM in section 2.2.

The Higgs boson is an important element of the Standard Model. By means of spontaneous symmetry breaking the Higgs mechanism provides mass to particles. The Higgs boson remains the last undiscovered particle predicted by the Standard Model. Supersymmetry (SUSY) is considered as a viable extension of the Standard Model. In SUSY a symmetry between fermions and bosons is assumed by introducing superpartners to the known elementary particles. The Minimal Supersymmetric extension of the Standard Model (MSSM) is the SUSY model with the minimal number of extra parameters. The Higgs sector of the MSSM predicts the existence of five physical Higgs particles, three neutral and two charged Higgs, and is a special case of the Two Higgs Doublet Model (2HDM). SUSY, MSSM and 2HDM are presented in subsection 2.2.1.

In the basic Standard Model neutrinos are assumed to be massless. However, recent experiments with neutrinos demonstrate [7] that neutrinos oscillate between different flavor states, which must therefore have different masses. Neutrino masses can be described by an extension of the Standard Model as described in subsection 2.2.2.

To explore the validity of the Standard Model and investigate possible manifestations of new physics, such as neutrino oscillations and supersymmetry, huge particle physics experiments are being built around the world. This thesis describes analysis work done to investigate two of these experiments, both...
based on the use of accelerators at CERN, the European Laboratory for Particle Physics near Geneva in Switzerland.

The first particle physics experiment discussed in this thesis is a long baseline, high energy, tau neutrino appearance experiment, used to probe neutrino oscillations. A description of the CERN Neutrino Beam to Gran Sasso (CNGS) is given in chapter 3. The studies reported in Papers I and II have been performed to investigate an earlier proposal of a new tau neutrino detection concept, intended for use in the CNGS.

The second particle physics experiment investigated in this thesis is ATLAS, a general-purpose detector that is built with the aim to detect a wide range of signatures from non-SM physics. The detection of the Higgs boson and non-SM particles like supersymmetric particles and the charged Higgs boson occupy a prominent place in the ATLAS physics program. LHC and ATLAS, and in particular the ATLAS Inner Detector (ID), will be described in chapter 4. Paper III describes software development work done to improve the performance of this Inner Detector.

In Paper IV is described a study of the possibility to discover the charged Higgs boson through its decay to SUSY particles using a Monte Carlo simulation code of the ATLAS detector.

Chapter 5 contains a summary of each Paper included in this thesis. The conclusions and an outlook are given in chapter 6.
2 Theoretical background

In this chapter a brief introduction to the physics of this thesis is given. The theoretical model of the fundamental forces and particles, known as the Standard Model (SM), is briefly introduced in section 2.1. The Higgs mechanism by which the fundamental particles of the SM acquire mass is the subject of section 2.1.5.

The principle of Supersymmetry is one of the most promising theoretical developments beyond the SM. The Minimal Supersymmetric extension of the Standard Model (MSSM) is the simplest supersymmetric theory that reproduces the results of the SM at low energies. The MSSM together with its Higgs sector is introduced in section 2.2.1.

In section 2.2.2 the principles of oscillating neutrinos are given as another example of new physics.

2.1 The Standard Model

The Standard Model (SM) of high energy physics has been enormously successful in explaining and predicting the results of high energy physics experiments.

The SM is based on quantum field theory [8]. It assumes the existence of fermion fields representing matter and from the assumption of gauge invariance of the theory gauge fields emerge that carry interactions. The fields are represented by physically fundamental point-like particles with certain properties, quantum numbers. One quantum number is called “spin” and is normally described as the internal angular momentum of the particle. However, unlike the spin of an object in the classical world, the spin of elementary particles is quantized\(^1\).

For all SM particles there exists an antiparticle, with the same mass and the same absolute values of all the quantum numbers but with opposite sign.

---

\(^1\)Elementary particles with non-zero spin are deflected in distinct directions by a magnetic field. This suggests their spin is quantized. For a spin \(1/2\) particle with two possible spin directions the spin components are numerically either \(\hbar/2\) or \(-\hbar/2\), said to have spin \(1/2\) or \(-1/2\) [9].
2.1.1 Fermions

The elementary matter particles are leptons and quarks, obeying the Fermi-Dirac statistics\(^2\) and are therefore called fermions \([9]\). They have spin 1/2. There are six leptons: the electron (\(e\)), muon (\(\mu\)) and tau (\(\tau\)) lepton and their associated neutrinos (\(\nu_e\), \(\nu_\mu\) and \(\nu_\tau\)), ordered in three families (or generations): \((e, \nu_e)\), \((\mu, \nu_\mu)\) and \((\tau, \nu_\tau)\). There are also six quark flavors: up (\(u\)), down (\(d\)), strange (\(s\)), charm (\(c\)), bottom (\(b\)) and top (\(t\)). Also the quarks are ordered in three families as can be seen in table 2.1 where the masses and electric charges of the fermions are listed.

<table>
<thead>
<tr>
<th>Family</th>
<th>I mass (MeV)</th>
<th>II mass (MeV)</th>
<th>III mass (GeV)</th>
<th>Q ((q_e))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(e)</td>
<td>0.51</td>
<td>(\mu) 105.66</td>
<td>(\tau) 1.777</td>
<td>−1</td>
</tr>
<tr>
<td>(\nu_e)</td>
<td>&lt; 3 \cdot 10^{-6}</td>
<td>(\nu_\mu) &lt; 0.19</td>
<td>(\nu_\tau) &lt; 0.018</td>
<td>0</td>
</tr>
<tr>
<td>Quarks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(u)</td>
<td>≈ 350</td>
<td>(c) ≈ 1500</td>
<td>(t) 178.0 ± 4.3</td>
<td>+2/3</td>
</tr>
<tr>
<td>(d)</td>
<td>≈ 350</td>
<td>(s) ≈ 500</td>
<td>(b) ≈ 4.5</td>
<td>−1/3</td>
</tr>
</tbody>
</table>

Table 2.1: The three families of fermions (the fundamental spin 1/2 particles of the SM). The lepton masses do not represent the full experimental precision. See \([10]\) for more exact data. For all quark masses except the top quark, the masses are those inferred from models of the hadron spectrum, i.e. the effective quark masses inside the hadrons (called “constituent” quark masses) \([10]\). The top quark mass is from direct observation of top events \([11]\). In the last column their electrical charges are shown.

2.1.2 Bosons

The matter particles of table 2.1 interact with each other by exchanging messenger particles. There are four known interactions (or forces), each associated with an integer-spin particle which obey Bose-Einstein statistics\(^3\) and are therefore called bosons \([9]\).

Due to the electromagnetic force all charged particles interact with each other by exchanging photons, \(\gamma\). The massless and chargeless nature of the photon makes the strength of the force to be proportional to \(1/r^2\), where \(r\) is the distance between two charged particles.

The weak interaction can cause many types of reactions by the mediation of the massive \(W^\pm\) and \(Z^0\) bosons between the fermions. Since the field quanta

---

\(^2\)A system of identical particles obeying Fermi-Dirac statistics is totally anti-symmetric under the interchange of any pair, i.e. they anti-commute.

\(^3\)A system of identical particles obeying Bose-Einstein statistics is totally symmetric under the interchange of any pair, i.e. they commute.
of the weak force are heavy the Heisenberg uncertainty relation, \( \Delta p \Delta x \geq \frac{1}{2} \hbar \), limits the effective range of the weak interaction to \( \sim 10^{-18} \) m. In the basic SM, without neutrino masses, the lepton numbers are always conserved in weak interactions. This means that in a purely leptonic vertex where a \( W^\pm \) is absorbed or emitted it can only couple to a charged lepton and its corresponding neutrino from the same generation. For a hadronic vertex a quark change across the generations is however possible. This is allowed because the \( W^\pm \) boson couples not to the mass eigenstates of the quarks in the lower row in Table 2.1, but to linear combinations of these, given by the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix, \( V_{ij} \):

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix}
= 
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}.
\] (2.1)

The non-zero off-diagonal elements of the CKM matrix allow flavor transitions between families for the charged current of the weak force. Flavor Changing Neutral Currents (FCNC), i.e. generation transitions using the \( Z^0 \) boson as mediator, is however forbidden at tree level in the SM.

The quarks are welded together into hadrons by the exchange of eight massless gluons, \( g \), the messenger particles of the strong force. All quarks carry a quantum number called color charge. Any quark type can exist in three different color states: red, green or blue. The gluons also carry the color charge, thus couple to other gluons and therefore the energy needed to separate two quarks grows linearly with \( r \) at large distances (where \( r \) is the distance between the two quarks.). This is why quarks are never observed as free particles. They merge into hadrons so that the combinations always are colorless and have an integer electric charge (as seen in Table 2.1 quarks have fractions of electric charge). Three quarks can combine into a baryon or one quark and an antiquark can combine into a meson. One example of a baryon is the proton consisting of two \( u \) quarks and one \( d \) quark giving an electrical charge of \( +1 \) and since all three quarks have different color the proton is colorless.

The fourth interaction, the gravity force, has not yet been possible to incorporate into the SM. Gravity is very weak and negligible at the scale of high energy physics experiments. The messenger particle has been given the name graviton, \( G \).

There is one more boson in the SM, the Higgs boson. This boson is associated with the Higgs mechanism, proposed to provide masses to the fundamental particles of the SM (see section 2.1.5).

\(^4\) All quantum corrections are neglected.

\(^5\) A colorless state, or the color “white”, can be achieved with the combination of all three colors; red, green and blue or of one color and its anticolor, e.g. green and antigreen.
In table 2.2 all the bosons of the SM are listed.

<table>
<thead>
<tr>
<th>Interaction or Mechanism</th>
<th>name</th>
<th>symbol</th>
<th>spin</th>
<th>mass (GeV)</th>
<th>Q (q_e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>photon</td>
<td>γ</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Weak force</td>
<td>W±</td>
<td>1</td>
<td>80.419 ± 0.056</td>
<td>±1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z^0</td>
<td>1</td>
<td>91.1882 ± 0.0022</td>
<td>±1</td>
<td></td>
</tr>
<tr>
<td>Strong force</td>
<td>gluons</td>
<td>g</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Gravity</td>
<td>gravitons</td>
<td>G</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Higgs mechanism</td>
<td>Higgs</td>
<td>H</td>
<td>0</td>
<td>114.4 &lt; m_H &lt; 251</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.2: The bosons of the SM. These integer spin particles are responsible for the four fundamental interactions in nature and the Higgs mechanism. The masses of the force bosons are taken from [10]. The lower mass limit of the Higgs boson comes from direct measurements [13] and the upper mass limit comes from an electroweak fit with the latest top mass used [11].

2.1.3 Gauge Interactions

To mathematically describe the particles and the interactions of the SM the Lagrangian field theory formalism is used. Here the equations of motion are derived from Lagrangian densities, \( \mathcal{L} \), using the Euler-Lagrange equation [14]. For example, the equations of motion describing the time evolution of a free massless charged fermion \( \ell \) and its associated neutrino \( \nu \) are derived from the free lepton Lagrangian density 6

\[
\mathcal{L}_{lep}^0 = i \left( \bar{\psi} \gamma \nabla \psi + \bar{\psi} \gamma \nabla \nu \right), \tag{2.2}
\]

where \( \psi'(x) \) and \( \psi''(x) \) are complex spinors describing the state of the charged lepton and the state of the neutrino, respectively. Since observables depend on \( |\psi|^2 \), we can demand the theory to be invariant under complex gauge 7 transitions [15],

\[
\psi(x) \rightarrow \psi'(x) = e^{i \chi(x)} \psi(x), \tag{2.3}
\]

called local gauge transformations, as the transition factors, \( \chi \), may depend on the space-time vector, \( x \). To guarantee that the values of physical measurable quantities do not change in local gauge transformations the equations of motion must remain unchanged and therefore also the Lagrangian.

6Here two definitions for the \( \gamma \)-matrices are used: \( \bar{\psi} \equiv \psi^\dagger \gamma^0 \) and \( \gamma^\mu \partial_\mu \) [15].

7Gauge is another word for “phase” [14].
Interactions are included into the theory with the *gauge principle*. For each interaction the fermions follow a type of symmetry. There is one local gauge transformation (of the same form as eq. (2.3)) associated with each type of symmetry. The gauge principle makes the theory invariant under these transformations by adding interaction terms to the Lagrangian. These terms include spin 1 fields (i.e. gauge bosons) with transformation properties defined to make the Lagrangian invariant under the corresponding transformation. The terms also include generators for the corresponding symmetry and the coupling strengths for the interactions.

In the SM the electromagnetic force, described by a U(1) symmetric gauge theory called Quantum Electro-Dynamics (QED), is connected with the weak force, associated with an SU(2) symmetry, into the *electroweak* interaction, associated with a U(1)×SU(2) symmetry (this unification will be described further in section 2.1.4).

The generator of the U(1) symmetry is a single number, called hypercharge and denoted \(Y\), the gauge boson required is called \(B_\mu\) and the coupling strength is labeled \(g_1\). The generators for the SU(2) group are the three \(2 \times 2\) Pauli spin matrices, \(\tau_i, i = 1, 2, 3\). The associated gauge bosons necessary to maintain the invariance of the theory are called \(W_\mu^i\) and the coupling strength is labeled \(g_2\).

As mentioned in section 2.1.2 the quarks and the gluons carry color charge. This is described in an SU(3) symmetric theory, called Quantum Chromo-Dynamics (QCD), describing the interactions due to the strong force. For SU(3) there are 8 generators, simple \(3 \times 3\) generalizations of the Pauli matrices [15], called \(\lambda_a, a = 1, \ldots, 8\), and the eight associated gauge bosons are labeled \(G_\mu^a\). The coupling strength for the strong interaction is called \(g_3\).

The three interaction terms introduced by the invariances described above are included in the Lagrangian by exchanging the derivative \(\partial_\mu\) in (2.2) with a covariant derivative \(D_\mu\):

\[
\partial_\mu \to D_\mu \equiv \partial_\mu - ig_1 \frac{Y}{2} B_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu - ig_3 \frac{\lambda_a}{2} G^a_\mu, \quad (2.4)
\]

where summation over repeated indices is used and where the last term appears for quarks only.

Fermions can be either *doublets* or *singlets* under an SU(2) transformation. The doublets follow an SU(2) symmetry, i.e. they can transform into its partner or into itself while singlets do not transform at all under an SU(2) transformation. Experimentally it has been shown that left handed charged leptons transform into left handed neutrinos of the same family under charged weak interaction, while right handed leptons do not couple to \(W^\pm\) at all. In the basic SM neutrinos have no mass so the right handed neutrinos do not couple to any of the known fundamental forces of the nature. The \(\nu_R^l\) are therefore

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8A left-handed particle has its spin in the opposite direction of its momentum.
assumed not to exist. So the electroweak SU(2) doublets and singlets of the leptons are

\[
\begin{align*}
\left( \begin{array}{c} \psi_{\nu e} \\ \psi_{\mu e} \end{array} \right)_L, & \left( \begin{array}{c} \psi_{\nu e} \\ \psi_{\tau e} \end{array} \right)_L, \psi_{e-}^R, \psi_{\mu-}^R, \psi_{\tau-}^R, \\
\end{align*}
\]

where the \(x\) dependencies of the spinors are left out for simplicity. Also the quarks doublets and singlets are grouped in three families

\[
\begin{align*}
\left( \begin{array}{c} \psi_u \\ \psi_d \end{array} \right)_L, & \left( \begin{array}{c} \psi_c \\ \psi_s \end{array} \right)_L, \left( \begin{array}{c} \psi_t \\ \psi_b \end{array} \right)_L, \psi_{d}^R, \psi_{u}^R, \psi_{s}^R, \psi_{c}^R, \psi_{b}^R, \psi_{t}^R. \\
\end{align*}
\]

The summation over the fermion families can be defined as \(f_k, k = 1, 2, 3\). For example

\[
f_1 = \left\{ \left( \begin{array}{c} \psi_{\nu e} \\ \psi_{e-} \end{array} \right)_L, \psi_{e-}^R, \left( \begin{array}{c} \psi_u \\ \psi_d \end{array} \right)_L, \psi_{d}^R, \psi_{u}^R \right\}. 
\]

With the convention that the terms in \(D_\mu\) only act on fermion states of the same matrix form (e.g. the last term in (2.4) \(\lambda_a G_\alpha\) is a \(3 \times 3\) matrix in color space and therefore only effects the quarks), the fermionic Lagrangian density can be written in the comprehensive form;

\[
\mathcal{L}_{\text{ferm}} = \sum_{k=1}^{3} \sum_{f_k} i \bar{f}_k \mathcal{D} f_k. 
\]

This Lagrangian density describes both free fermion fields and the interaction between the fermion fields and the gauge fields, where \(g_1, g_2\) and \(g_3\) are the coupling strengths of these interactions.

### 2.1.4 Electroweak Unification

If \(W_{1\mu}\) and \(W_{2\mu}\) (in eq. (2.4)) would be interpreted as the gauge fields of the charged weak interactions (with \(W^\pm\) as bosons) and \(W_{3\mu}\) as the gauge field of the neutral weak interaction (with \(W^0\) as the force mediating boson) the charged and neutral weak interactions would have the same strengths, which is experimentally not observed. Instead it turns out [8] that the gauge fields \(B_\mu\) and \(W_{3\mu}\) combine into the physical photon and \(Z^0\) boson fields;

\[
\begin{align*}
A_\mu &= \sin \theta_W W_{3\mu} + \cos \theta_W B_\mu, \\
Z_\mu &= \cos \theta_W W_{3\mu} - \sin \theta_W B_\mu, 
\end{align*}
\]

If \(W_{1\mu}\) and \(W_{2\mu}\) (in eq. (2.4)) would be interpreted as the gauge fields of the charged weak interactions (with \(W^\pm\) as bosons) and \(W_{3\mu}\) as the gauge field of the neutral weak interaction (with \(W^0\) as the force mediating boson) the charged and neutral weak interactions would have the same strengths, which is experimentally not observed. Instead it turns out [8] that the gauge fields \(B_\mu\) and \(W_{3\mu}\) combine into the physical photon and \(Z^0\) boson fields;

\[
\begin{align*}
A_\mu &= \sin \theta_W W_{3\mu} + \cos \theta_W B_\mu, \\
Z_\mu &= \cos \theta_W W_{3\mu} - \sin \theta_W B_\mu, 
\end{align*}
\]

This equation describes both free fermion fields and the interaction between the fermion fields and the gauge fields, where \(g_1, g_2\) and \(g_3\) are the coupling strengths of these interactions.
and $W_{1\mu}$ and $W_{2\mu}$ combine into the physical charged weak boson fields

$$W_+^\mu = \sqrt{\frac{T}{2}} (W_{1\mu} - iW_{2\mu}) \ , \quad (2.11)$$

$$W_-^\mu = \sqrt{\frac{T}{2}} (W_{1\mu} + iW_{2\mu}) \ . \quad (2.12)$$

The angle $\theta_W$ in (2.9) and (2.10) is known as the electroweak mixing angle or the Weinberg angle. It can be shown that for $A_\mu$ to have the couplings of a photon the coupling constants must follow [8], [15]

$$g_1 \cos \theta_W = g_2 \sin \theta_W = e \ . \quad (2.13)$$

Here the coupling strengths of the weak interactions $g_1$ and $g_2$ are connected to the coupling strength of the electromagnetic interaction $e$. The precise agreement of the predictions from this unified theory and experimental results from the measurable values from $Z^0$ boson experiments is a great triumph of the electroweak unification theory. However, the fact that mass terms like $m\bar{\psi}\psi$, $m_W^2 W_\mu W^{\mu}$ and $m^2_{Z\mu} Z^{\mu\mu}$ in the Lagrangian would break the gauge invariance [8] conflicts with experimental measurements of massive charged fermions and heavy $W^\pm$ and $Z^0$ bosons.

2.1.5 The Higgs Mechanism

The SM introduces the masses of the charged fermions and heavy bosons into the SU(2)×U(1) gauge-invariant theory by a mechanism that breaks the symmetry spontaneously. Spontaneous symmetry breaking can occur if the ground state of a system is degenerate. Then the arbitrary choice of one of the degenerate ground states causes the symmetry breaking9. In field theory the ground state is the vacuum. To break the SU(2)×U(1) symmetry spontaneously a weak isospin doublet with components of scalar Higgs fields with non-vanishing and invariant vacuum expectation values, is introduced10:

$$\phi = \left( \begin{array}{c} \phi_0 \\ \phi_i \end{array} \right) = \frac{1}{\sqrt{2}} \left( \begin{array}{c} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{array} \right) \quad (2.14)$$

The higgs potential is then

$$V_H(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \ , \quad (2.15)$$

where $\lambda$ must be positive to keep the potential from becoming negative for large $\phi$ so that the vacuum is stable. To achieve a non-unique vacuum state,

9Unlike normal symmetry breaking where a non-invariant asymmetric term is added to the Lagrangian.

10The $\times$ dependencies of the fields are left out for simplicity.
\( \mu^2 \) is chosen negative which gives a condition of the minimum of \( V_H(\phi) \):

\[
V_H(\phi) = (V_H)_{\text{min}} \iff \phi^\dagger \phi = \frac{1}{2} (\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = -\frac{\mu^2}{2\lambda}.
\] (2.16)

As seen the ground state is degenerate and by choosing one of the possibilities:

\[
\phi_1 = \phi_2 = \phi_4 = 0, \quad \phi_3 = -\frac{\mu}{\lambda} \equiv v,
\] (2.17)

the SU(2) \( \times \) U(1) symmetry is spontaneously broken. In eq. (2.17) \( v \) is defined to be the vacuum expectation value of \( \phi_3 \).

In particle physics the derivation of physics from the Lagrangian density using the Euler-Lagrange equation is practically impossible due to too complicated calculations. Instead perturbation theory is used to determine the particle spectra and we will see that this approach reveals the masses of the heavy bosons. The expansion of the Higgs field around the vacuum is

\[
\phi_0^{\text{exp}} = \frac{1}{\sqrt{2}} \left( \begin{array}{c} 0 \\ v + h(x) \end{array} \right).
\] (2.18)

The kinetic and potential energy terms added to the Lagrangian from the Higgs field are

\[
\mathcal{L}_{\text{Higgs}} = (\partial_{\mu} \phi)^\dagger (\partial^{\mu} \phi) - V_H(\phi).
\] (2.19)

The kinetic energy terms breaks the SU(2) \( \times \) U(1) symmetry so again the partial derivative has to be replaced with the covariant partial derivative, \( \partial_{\mu} \rightarrow D_{\mu} \). Only the first three terms of eq. (2.4) are used for \( D_{\mu} \) since the SU(3) symmetry is not involved here. Inserting \( \phi_0^{\text{exp}} \) into \( \mathcal{L}_{\text{Higgs}} \), writing the Pauli spin matrices explicitly and using the relation

\[
-\mu^2 = \lambda v^2
\]

from eq. (2.17) when writing \( V_H(\phi_0^{\text{exp}}) \) explicitly the Higgs Lagrangian density is

\[
\mathcal{L}_{\text{Higgs}} = (v + h)^2 \left( \frac{g_2^2 Y}{8} B_{\mu} B^\mu - \frac{g_2 g_1}{4} W_3^\mu W_3^\mu + \frac{g_2^2}{8} W_3^\mu W_3^\mu \right)
+ (v + h)^2 \frac{g_2^2}{8} (W_1^\mu W_1^\mu + W_2^\mu W_2^\mu)
+ \frac{1}{2} (\partial^\mu h) (\partial_\mu h) + \frac{1}{2} \lambda v^2 (v + h) - \frac{1}{4} \lambda (v + h)^2.
\] (2.20)

From equations (2.11) and (2.12) we see that the second row in (2.20) includes a mass term for the weak charged bosons, \( \frac{1}{2} v g_2^2 W_3^\mu W_3^\mu \), which reveal that the charged \( W \) acquire a mass \( m_{W^\pm} = \frac{1}{2} v g_2 \). If we choose \( Y = 1 \) the first row in (2.20) can be written as

\[
\frac{1}{8} v^2 (g_2 W_3^\mu - g_1 B_\mu)^2 + 0 \left( g_2 W_3^\mu + g_1 B_\mu \right)^2,
\] (2.21)
where the second term is added for identification with the physical fields $Z_\mu$ and $A_\mu$ that should have mass terms $\frac{1}{2}m_Z^2 Z_\mu Z^\mu$ and $\frac{1}{2}m_A^2 A_\mu A^\mu$ respectively:

\[ A_\mu = \alpha_2 W_3 \mu + \alpha_1 B_\mu \quad \text{with} \quad m_A = 0 , \]  
(2.22)

\[ Z_\mu = \alpha_2 W_3 \mu - \alpha_1 B_\mu \quad \text{with} \quad m_Z = \frac{1}{2}v\sqrt{g_1^2 + g_2^2} , \]  
(2.23)

where $\alpha_1 = g_1/\sqrt{g_1^2 + g_2^2}$ and $\alpha_2 = g_2/\sqrt{g_1^2 + g_2^2}$ due to normalization [14]. The relations in (2.22) and (2.23) are equivalent with (2.9) and (2.10) in case $g_2/g_1 = \tan \theta_W$, which has already been seen in the electroweak unification condition (2.13). This gives a relation between $m_{W^\pm}$ and $m_Z$ that is normally expressed with the parameter

\[ \rho \equiv \frac{m_{W^\pm}^2}{m_Z^2 \cos^2 \theta_W} = 1 . \]  
(2.24)

The prediction that $\rho = 1$ agrees to good precision with experimental data and is one of the SM’s great triumphs. On the third line of (2.20) there is also a second order mass term for the Higgs field $h$ which means that the Higgs field has another manifestation as a physical massive Higgs particle. The mass of the neutral Higgs boson can be derived to depend on the vacuum expectation value $v$ and on the perturbation parameter $\lambda$, $m_h^2 = 2v^2 \lambda$ [14]. By introducing a coupling between the Higgs field and fermions one can also include the mass terms for fermions. The mass of each fermion is determined by the corresponding coupling strength [14].

### 2.2 Beyond the Standard Model

The Standard Model has been extremely successful in describing the experimentally observed particle physics phenomenology up to the electroweak energy scale of the order of 100 GeV. However there are some theoretical problems [16] with the SM indicating that a more general theory would be needed. For example since the SM does not manage to describe gravity there must be another theory at the Planck scale $M_P = (8\pi G_{\text{Newton}})^{-1/2} = 2.4 \cdot 10^{18}$ GeV. The so called hierarchy problem suggests that the SM fails even before the Planck scale. Due to the uncertainty principle virtual particles with arbitrary high energy can be created in loop diagrams. The mass of scalar fields, like the Higgs mass, is affected by quantum mechanical loop corrections that can be of the order of the energy cut off scale of the theory. If the SM would hold up to the Planck scale the Higgs field mass would be of the order of $M_P$. This is in disagreement with the fact that the Higgs field mass term, $\mu^2$, should be of the order of the energy of the gauge bosons for which it generates masses.
for, i.e. $\sim 100$ GeV. Another dissatisfaction with the SM is that it contains at least 19 arbitrary parameters and it does not explain its quantum numbers or why there are three fermion families. The three interaction coupling strengths of the SM are energy dependent. Using the SM theory the extrapolation of these couplings do not meet in one unique energy. A unification of the coupling strengths is wanted by the attempt of formulating a Grand Unified Theory (GUT) in which the SU(3)$_C$, SU(2)$_W$ and U(1)$_Y$ symmetries of the SM become sub-groups of a larger unified group. At sufficiently high energies these three interactions would then be described by one single coupling constant $g_G$.

2.2.1 SUSY, MSSM and 2HDM

A good candidate for solving the hierarchy problem of the fermion loop corrections in the Higgs field mass is Supersymmetry (SUSY). SUSY is a symmetry that connects particles that differ by half a unit spin but have the same mass and all the other quantum numbers equal. This predicts a bosonic supersymmetric partner for each SM fermion and a fermionic superpartner for each SM boson. SUSY solves the hierarchy problem since the fermion and boson loop corrections in the Higgs boson mass have opposite signs and cancel each other out naturally.

The Minimal Supersymmetric Standard Model (MSSM) has the minimal particle content of all SUSY models. In MSSM all SM fermions (of spin 1/2) have a scalar (spin 0) sfermion (“s” for scalar) partner. Even though the spin 0 sfermions cannot have “handedness” there exist superpartners for both right and left handed fermions. The sleptons are the selectrons ($\tilde{e}_L$, $\tilde{e}_R$), the smuons ($\tilde{\mu}_L$, $\tilde{\mu}_R$), the staus ($\tilde{\tau}_L$, $\tilde{\tau}_R$) and the sneutrinos ($\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$). The tilde is used to denote the superpartner of a SM particle, so the squarks are $\tilde{q}_L$ and $\tilde{q}_R$ where $q = u, d, s, c, b$ and $t$. In MSSM all gauge bosons with spin 1 have spin 1/2 gaugino partners. For example the gluons $g$, the mediators of the SU(3)$_C$ color gauge interaction, have the spin 1/2 gluinos $\tilde{g}$ as superpartners. The mediators of the electroweak gauge symmetry SU(2)$_W \times$ U(1)$_Y$, $W^+$, $W^-$ and $B^0$ have spin 1/2 superpartners, $\tilde{W}^+$, $\tilde{W}^0$, $\tilde{W}^-$ and $\tilde{B}^0$ called winos and bino. These Gauge Eigenstates do not mix in the same way as the SM gauge bosons due to symmetry breaking of MSSM, as will be discussed later.

In the MSSM the Higgs sector is extended from one to two complex Higgs doublet fields. This is a special case of the two Higgs Doublet Model (2HDM). One strong justification for two doublets in the MSSM Higgs sector is that $\rho$ (see eq. (2.24)) can then be shown to be close to unity [17], which is in agreement with experimental results (in the SM $\rho = 1$, see end of section 2.1.5). Another experimental fact that has to be satisfied by the 2HDM is that Flavor Changing Neutral Currents (FCNC) are highly suppressed. FCNC vanish at
tree level if it is required that one of the Higgs doublets, $H_u$, couples only to up-type quarks (up, charm, top) and the other doublet, $H_d$, couples only to down-type quarks (down, strange, bottom) and charged leptons [18]. $H_u$ and $H_d$ both have two weak isospin components with electric charges either 1 or 0\(^1\):

$$H_u = \begin{pmatrix} H^+_u \\ H^0_u \end{pmatrix}, \quad H_d = \begin{pmatrix} H^0_d \\ H^-_d \end{pmatrix}. \quad (2.25)$$

Each Higgs doublet has a vacuum expectation value, $v_u = \langle H^0_u \rangle$ and $v_d = \langle H^0_d \rangle$, and the ratio is written as

$$\tan \beta \equiv \frac{v_u}{v_d}. \quad (2.26)$$

The fermionic superpartners of these Higgs scalars are called higgsinos. For the weak isospin components in eq. (2.25) the supersymmetric partners are $\tilde H^+_u, \tilde H^0_u, \tilde H^0_d$ and $\tilde H^-_d$.

Since no supersymmetric particles have been observed so far they cannot have the same mass as their SM partners, i.e. SUSY must be a broken symmetry. In MSSM SUSY-breaking terms are introduced “by hand” into the Lagrangian so that the SU(3)\(\times\)SU(2)\(\times\)U(1) gauge invariance is conserved [10].

When the electroweak symmetry is broken 3 out of the initial 8 degrees of freedom of the two complex SU(2)\(_L\)-doublets in eq. (2.25), are used to generate the masses to the $W^\pm$ and $Z^0$ bosons. This leaves five physical Higgs bosons states. Two of them, $H^0$ and $h^0$, are CP-even scalars, one Higgs boson, $A^0$, is CP-odd and the last two Higgs bosons are two charged scalars, $H^\pm$.

In MSSM the potential of the Higgs fields is expanded around its minimum to extract masses in a similar way as was done in the SM (see 2.1.5). The tree level masses of these mass eigenstates can be shown to be related in the following way [18]

$$m^2_{H^\pm} = m_A^2 + m_W^2$$

$$m^2_{H^0,H^0} = \frac{1}{2} \left( m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2m_Z^2\cos^2 2\beta} \right). \quad (2.28)$$

This shows that only two parameters, generally chosen to be the mass of the CP-odd Higgs boson, $m_A$, and the ratio between the vacuum expectation values of the two Higgs doublets, $\tan \beta$, determine the structure of the Higgs sector at tree level. It can be shown from eq. (2.28) that the mass of $h^0$ is bounded by

$$m_{h^0} < |\cos 2\beta| m_Z$$

at tree-level, i.e. the lightest Higgs boson would have been detectable by

\(^1H_u$ and $H_d$ are sometimes also called $H_1$ and $H_2$ respectively.
LEP2. This apparent contradiction is avoided by large radiative corrections.

Due to electroweak symmetry breaking the Higgsinos and electroweak gauginos mix with each other. The neutral Higgsinos ($\tilde{H}_u^0$ and $\tilde{H}_d^0$) and the neutral gauginos ($\tilde{B}^0$ and $\tilde{W}^0$) combine to form four neutral mass eigenstates called neutralinos, denoted $\tilde{\chi}_i^0$ ($i = 1, 2, 3, 4$). The charged Higgsinos ($\tilde{H}_u^+$ and $\tilde{H}_d^-$) and winos ($\tilde{W}^+$ and $\tilde{W}^-$) mix to form two charged mass eigenstates called charginos, denoted $\tilde{\chi}_i^\pm$ ($i = 1, 2$).

The mixing of the squarks and sleptons is proportional to the mass of the corresponding SM fermion. That is why the mixing of the first and second-family squarks and sleptons can be assumed to be negligible. The mass eigenstates and the gauge eigenstates of the MSSM are listed in Table 2.3.

<table>
<thead>
<tr>
<th>Names</th>
<th>spin</th>
<th>Mass Eigenstates</th>
<th>Gauge Eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>$h^0, H^0, A^0, H^\pm$</td>
<td>$H_u^0, H_d^0, H_u^+, H_d^-$</td>
</tr>
<tr>
<td>squarks</td>
<td>0</td>
<td>$\tilde{u}_L \tilde{u}_R \tilde{d}_L \tilde{d}_R$</td>
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</tr>
<tr>
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<td></td>
<td>$\tilde{s}_L \tilde{s}_R \tilde{c}_L \tilde{c}_R$</td>
<td>$\tilde{s}_L \tilde{s}_R \tilde{c}_L \tilde{c}_R$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\tilde{t}_1 \tilde{t}_2 \tilde{b}_1 \tilde{b}_2$</td>
<td>$\tilde{t}_1 \tilde{t}_2 \tilde{b}_1 \tilde{b}_2$</td>
</tr>
<tr>
<td>sleptons</td>
<td>0</td>
<td>$\tilde{e}_L \tilde{e}_R \tilde{\nu}_e$</td>
<td>$\tilde{e}_L \tilde{e}_R \tilde{\nu}_e$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\tilde{\mu}_L \tilde{\mu}<em>R \tilde{\nu}</em>\mu$</td>
<td>$\tilde{\mu}_L \tilde{\mu}<em>R \tilde{\nu}</em>\mu$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\tilde{\tau}_L \tilde{\tau}<em>R \tilde{\nu}</em>\tau$</td>
<td>$\tilde{\tau}_L \tilde{\tau}<em>R \tilde{\nu}</em>\tau$</td>
</tr>
<tr>
<td>neutralinos</td>
<td>1/2</td>
<td>$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$</td>
<td>$\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0$</td>
</tr>
<tr>
<td>charginos</td>
<td>1/2</td>
<td>$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$</td>
<td>$\tilde{W}^\pm, \tilde{H}_u^\pm, \tilde{H}_d^\mp$</td>
</tr>
<tr>
<td>gluino</td>
<td>1/2</td>
<td>$\tilde{g}$</td>
<td>$\tilde{g}$</td>
</tr>
<tr>
<td>gravitino</td>
<td>3/2</td>
<td>$\tilde{G}$</td>
<td>$\tilde{G}$</td>
</tr>
</tbody>
</table>

Table 2.3: The undiscovered particles of MSSM [18].

### 2.2.2 Oscillating Neutrinos

In the simplest form of the SM the neutrinos ($\nu_e, \nu_\mu$ and $\nu_\tau$) are assumed to be massless. The experimental upper limits on the neutrino masses are according to [10] $m_{\nu_e} \lesssim 3$ eV, $m_{\nu_\mu} \lesssim 190$ keV and $m_{\nu_\tau} \lesssim 18$ MeV. Even stronger limits come from cosmology; $\sum m_{\nu} \lesssim 1$ eV [19]. There is no known theoretical reason why neutrinos should have zero masses and it is not known what mechanism could generate their masses. If a term like $g_2 \bar{\psi}_\nu \phi \psi_\nu$ (where notations introduced in section 2.1 are used) is introduced into the Lagrangian the term would be a mass term of $\nu$ when the Higgs doublet, $\phi$, gets a vacuum expectation value. Then the neutrinos would have so called Dirac masses. Since
most models assume that right handed neutrinos do not exist (see discussion in section 2.1.3) other mechanisms capable to explain neutrino masses are suggested. Majorana masses would be generated from the mass term \( m \bar{\psi}^T \psi \), where \( c \) indicates the charge conjugate state. A fermion that has the property that its charge conjugate is equal to itself is called a Majorana fermion.

So, with or without right handed neutrinos it seems theoretically possible that neutrinos are massive. Some neutrino experiments have already shown evidence for neutrino oscillation [7] which is an effect caused by massive neutrinos. If neutrinos have masses the gauge eigenstates (\( \nu_e, \nu_\mu \) and \( \nu_\tau \)) are linear combinations of the mass eigenstates (\( \nu_1, \nu_2 \) and \( \nu_3 \)) [10];

\[
|\nu_\ell(t)\rangle = \sum_{m=1}^{3} U_{\ell m} |\nu_m\rangle, \quad \ell = e, \mu, \tau ,
\]

(2.30)

where \( U \) is the leptonic mixing matrix. Eq. (2.30) indicates that a flavor eigenstate \( \nu_\ell \) is with probability \( |U_{\ell 1}|^2 \) a \( \nu_1 \), \( |U_{\ell 2}|^2 \) a \( \nu_2 \) and \( |U_{\ell 3}|^2 \) a \( \nu_3 \). This implies that the flavor states transform into each other (or “oscillate”) as they propagate.

The neutrino oscillation probability

The probability for a neutrino to oscillate between different flavor states will now be derived. According to Schrödinger’s equation the time dependence of a mass eigenstate \( |v_m\rangle \), created at time \( t = 0 \), with mass \( M_m \) is [9],

\[
|v_m(t'_m)\rangle = e^{-iM_m t'_m} |v_m\rangle ,
\]

(2.31)

where \( t'_m \) is the time in the \( v_m \) frame and where \( \hbar \) is put to unity. The phase factor in eq. (2.31) may be rewritten in terms of the time \( t \) and the position \( L \) in the laboratory frame,

\[
e^{-iM_m t'_m} = e^{-i(E_m t - p_m L)} \approx e^{-i(E_m - p_m/c)t} .
\]

(2.32)

Here \( E_m \) and \( p_m \) are the energy and momentum for \( v_m \) in the laboratory frame. In the last step of eq. (2.32) the relativistic nature of the neutrinos is used and \( c \) is put to unity. Assume that \( \nu_\ell \) was produced with a definite energy, \( E \), so that all mass eigenstates have this common energy. Then \( p_m = \sqrt{E^2 - M_m^2} \approx E - \frac{M_m^2}{2E} \) so that the phase (2.32) becomes \( e^{-i(M_m^2/2E)L} \). When this phase factor is inserted in eq. (2.30) with eq. (2.31), the time dependence of the flavor eigenstates is given by

\[
|\nu_\ell(t)\rangle = \sum_{m=1}^{3} U_{\ell m} e^{-i(M_m^2/2E)L} |v_m\rangle , \quad \ell = e, \mu, \tau .
\]

(2.33)
In the SM, extended to include neutrino masses, the mixing matrix in eq. (2.30), $U$, is unitary. The mass eigenstates are thus superpositions of the flavor eigenstates:

$$|\nu_m\rangle = \sum_\ell U_{\ell m}^* |\nu_\ell\rangle, \quad m = 1, 2, 3.$$  (2.34)

If we combine eq. (2.34) with eq. (2.33) we see that after a time $t \neq 0$ the flavor state, $|\nu_\ell\rangle$, has turned into a superposition of all the flavors:

$$|\nu_\ell(t)\rangle = \sum_{\ell'} \left[ \sum_m U_{\ell m} e^{-i(M_m^2/2E)L} U_{\ell' m}^* \right] |\nu_{\ell'}\rangle.$$  (2.35)

The probability that the neutrino of flavor $\ell$ has oscillated to another state with flavor $\ell'$ after having traveled a distance $L$ is then

$$P(|\nu_\ell \rightarrow \nu_{\ell'}; L\rangle = |\langle \nu_{\ell'}|\nu_\ell(L)\rangle|^2 = \left| \sum_m U_{\ell m} e^{-i(M_m^2/2E)L} U_{\ell' m}^* \right|^2.$$  (2.36)

To achieve more handy expressions one can assume high degeneracy of two of the mass eigenstates while the third mass is much larger [10]; $|\Delta M_{21}^2| \ll |\Delta M_{32}^2|$ where $\Delta M_{mm}^2 \equiv M_m^2 - M_{m'}^2$. Then, if a neutrino oscillation experiment is designed so that $\Delta M_{21}^2 L/E$ is negligible but $\Delta M_{32}^2 L/E$ is not, an approximation of eq. (2.36) can be shown to be [20]

$$P(|\nu_\ell \rightarrow \nu_{\ell'}; L\rangle \approx |2U_{3\ell} U_{3\ell'}|^2 \sin^2 \left( \frac{\Delta M_{32}^2 L}{4E} \right).$$  (2.37)

If neutrinos are assumed to be Dirac particles the parameterization of the mixing matrix can be parameterized as [21]

$$U = \begin{pmatrix}
  c_{e\mu} c_{e\tau} & s_{e\mu} c_{e\tau} & s_{e\tau} e^{-i\delta} \\
  -s_{e\mu} c_{e\tau} - c_{e\mu} s_{e\tau} s_{\mu\tau} e^{i\delta} & -c_{e\mu} s_{e\tau} - s_{e\mu} c_{e\tau} s_{\mu\tau} e^{i\delta} & c_{\mu\tau} c_{e\tau} \\
  s_{e\mu} s_{e\tau} - c_{e\mu} c_{e\tau} s_{\mu\tau} e^{i\delta} & -c_{e\mu} s_{e\tau} - s_{e\mu} c_{e\tau} s_{\mu\tau} e^{i\delta} & c_{\mu\tau} c_{e\tau}
\end{pmatrix}.$$  (2.38)

Here the short notations $s_{\ell'\ell} = \sin \theta_{\ell'\ell}$ and $c_{\ell'\ell} = \cos \theta_{\ell'\ell}$ are used for sine and cosine of the mixing angle of the states with the flavor $\ell$ and $\ell'$. The CP-violation phase factor, $\delta$ is called the “Dirac phase”. Examining the prefactor in eq. (2.37) for the case when a muon neutrino ($\ell = \mu$) oscillates to a tau neutrino ($\ell' = \tau$) and using the experimental units ($\hbar \neq 1$, $c \neq 1$, $\Delta M_{12}^2$ in (eV/c$^2$), $L$ in km and $E$ in GeV), we get [20]

$$P(|\nu_\mu \rightarrow \nu_\tau; L\rangle = \cos^4 \theta_{e\tau} \sin^2 2\theta_{\mu\tau} \sin^2 \left( 1.267\Delta M_{32}^2 \frac{L}{E} \right).$$  (2.39)
This is the typical equation used for neutrino experiments of, for example, the long baseline type. An example, CNGS, will be discussed in chapter 3. The theory shown in this chapter only applies to neutrino oscillations in vacuum, but according to [20] matter effects on $\nu_\mu \leftrightarrow \nu_\tau$ oscillations are relatively small.
3 CNGS, tau-RICH and HPD

In 2006 CERN will start sending a high energy, high intensity $\nu_\mu$ beam to Gran Sasso located 120 km east of Rome. The neutrino beam CNGS (CERN Neutrino Beam to Gran Sasso) will have an energy between 5 and 30 GeV and will be produced by extracting a 450 GeV proton beam from the CERN SPS accelerator and having these protons interact with a fixed target. The secondary particles, mostly $\pi$ and K mesons, from these interactions will be focused into a 1 km long tunnel where the mesons will have time to decay according to

\begin{align}
\pi^\pm({\color{blue}-}) & \rightarrow \mu^\pm({\color{blue}-}) + \nu_\mu (\bar{\nu}_\mu), \\
K^\pm({\color{blue}-}) & \rightarrow \mu^\pm({\color{blue}-}) + \nu_\mu (\bar{\nu}_\mu).
\end{align}

Two muon detectors, separated 67 meters apart, will measure the direction and intensity of the muons, hence also the key parameters of the muon-neutrino beam toward the Gran Sasso Laboritories (LNGS). When the neutrino beam reaches Gran Sasso, at a 732 km distance from CERN, it will have a diameter of about two kilometers. A massive 1.8 kiloton emulsion/lead detector named OPERA (Oscillation Project with Emulsion-tRacking Apparatus), currently under construction in Gran Sasso, will detect the appearance of $\nu_\tau$ in the CNGS beam [22].

An alternative concept for detection of $\nu_\tau$ was suggested [23] which consists of 1300 0.58 m$^3$ large modules filled with C$_6$F$_{14}$ liquid, amounting to a total target mass of 1 kiloton. A $\tau$ lepton, produced in charged current interactions of a $\nu_\tau$ with a target nucleus will emit Cherenkov light in the C$_6$F$_{14}$ radiator. The Cherenkov photons focused by a spherical mirror onto a spherical photon detector surface according to the Ring Imaging Cherenkov (RICH) concept [24] would resolve the short $\tau$ track from longer background tracks [1], [4]. The $\nu_\tau$ experiment concept, called tau-RICH, and the investigation made with Monte Carlo simulations are described in Papers I and II. Cherenkov radiation from delta electrons would constitute a sever background that would render the detection of the millimeter-short tau track unfeasible [2].

A significant part of the job done in connection with the study of the tau-RICH involved also the development of Hybrid Photo Diodes (HPD). An HPD is a high sensitively photo-detector that can detect single photons. Its basic components are an active detection window, a vacuum tube and a silicon sen-
sor. When a photon hits somewhere on the detection window the photocath-
dode, deposited onto the inner side of the window, emits electrons according to
the photoelectric effect. The quantum efficiency, i.e. the probability that an
electron is emitted when a photon is absorbed by the photocathode, depends
on the energy of the photon. A potential difference and focusing electrodes
force the emitted photoelectrons through the vacuum to the silicon sensor.

The “Pad HPD”, under development at CERN [25], has a spherical detec-
tion window with an active diameter of 114 mm (∼ 5 inches) with a bialkali
photocathode. The field from focusing electrodes makes the photoelectrons
go in fountain shaped paths from the detection window to the silicon sensor,
demagnifying the picture 2.3 times. The silicon sensor is 50 mm in diameter
with 2048 pads, each $1 \times 1 \text{ mm}^2$ and is read out by multiplexed analogue elec-
tronics. Several Pad HPDs were successfully used in 2003 at CERN in a test
beam for aerogel radiators [5, 6].

The project resulted in a further development of a Pad HPD for Positron
Emission Tomography (PET) [26] and a 10-inch Pad HPD [27] to be used in
the Air Cherenkov Telescope CLUE [28].
4 LHC, ATLAS and ID

A new particle collider, the Large Hadron Collider (LHC), is being built in the existing LEP (Large Electron Positron collider) tunnel at CERN and will start its operation in 2007 [29]. Superconducting magnets in the LHC ring of about 8 Tesla will enable proton-proton collisions at energies 10 times greater than any previous machine.

The most important question left in the SM unanswered by the experiments at LEP is the mechanism which gives mass to matter. Theory predicts that at around an energy of 1 TeV the mechanism is manifested by the Higgs particle (see section 2.2.1) which can be produced at LHC. Protons are complex objects with energy shared between quarks and gluons. A collision energy of 14 TeV is needed to cover the possible energy of the Higgs particle. Two counter-rotating proton beams of 7 TeV each collide head on at four collision points around the LHC ring. The protons are grouped in bunches each

![Figure 4.1: At one collision point of LHC the ATLAS experiment will collect data from pp collision events.](image)

with $10^{11}$ protons, with a bunch length of 75 mm and with a bunch radius of 18 $\mu$m [29]. The bunches will collide every 25 ns in the collision points. The target luminosity will be $10^{34}$ cm$^{-2}$s$^{-1}$ [29] which after one year of running will give an integrated luminosity of about 100 fb$^{-1}$. There will on average be about 23 collisions per bunch crossing.
ATLAS (A Torodial LHC ApparatuS) will be located at one of the collision points and collect data from particles that originate directly or indirectly from about a billion \((10^9)\) collisions per second. ATLAS is divided into several components each testing a set of particle properties. The tracking detector (also called the inner detector) is the innermost component of ATLAS enclosed by a solenoidal magnet. The inner detector is surrounded by the electromagnetic calorimeter, the hadron calorimeter and the muon detector. The muon detector is embedded in a toroidal magnetic field.

The inner detector (ID), closest to the interaction point, measures the direction, momentum and sign of charged particles with help of a solenoidal magnet\(^1\) and generating a magnetic field inside the coil. The ID consists of three sub-systems, each with finely subdivided sensors, ordered into layers. In the central barrel part of the detector the layers are parallel to the beam axis. In the end-cap parts the layers are placed radially to the beam axis. The small size and the knowledge of the precise position of the sensors make it possible to reconstruct trajectories of particles originating from the \(pp\) collisions. The Pixel detector (the three innermost rings in Figure 4.2 b) that is the innermost part of the ID detects the passage of charged particles with thin layers of small rectangular shaped silicon pixel sensors\(^2\). Thanks to the high resolution of the pixel detector and the small radius (4 cm) of the innermost pixel-barrel layer, the B-layer, the ID can see non zero impact parameters from short lived particles such as \(b\) quarks. After the Pixel detector the particles pass the Semi Conductor Tracker (SCT) (the four rings in the middle in Figure 4.2 b). The SCT consists of layers with two sets of narrow silicon strip sensors\(^3\), rotated by 2.3 degrees relative to each other which gives 3D-points from charge particle trajectories. The outermost tracking system of the ID is the Transition Radiation Tracker (TRT) (the outermost part in Figure 4.2 b) which consists of gas filled straws with a metal wire in the center\(^4\). When a charged particle transverses a straw charge is produce in the straw volume. The charge is drifted to electrodes by a high voltage applied between the metalized wall of the straw and the wire in the center. A precise position of the track is determined by the collection time of the charge.

With this design of the ID at least three pixel layers, four strip layers and approximately 36 gas straws are crossed by each track. Therefore about 10

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1The length of the solenoid is 5.3 m compared with the 6.7 m of the ID, causing an inhomogeneous magnetic field for the tracker. The \(z\)-component of the B-field varies from 2 Tesla in the center to 0.4 Tesla at the ends of the ID.
2The total number of thin rectangular silicon devices in the Pixel detector is approximately 140 million and the pixels' dimensions are 50 by 300 \(\mu\)m.
3The silicon strips of the SCT are several centimeters long but only 80 \(\mu\)m wide.
4The approximately 372,000 straws that the TRT consists of have internal diameters of 0.4 cm and are filled with 70% Xe, 20% CF\(_4\) and 10% CO\(_2\) gas. The copper wire has a radius of about 25 \(\mu\)m and the 85 \(\mu\)m thick straw wall is made of Kapton (C\(_3\)H\(_4\)O\(_2\)).
azimuthal position measurements from Pixel and SCT, with a precision of 10 - 20 $\mu$m, and about 36 points from TRT, with a precision of about 150 $\mu$m, are given for each charged particle. These signals are sorted into patterns produced by helical trajectories so that directions, momenta and charge for the particles can be determined (see Figure 4.2 c).

The event selection requires precise trajectory reconstruction. However, particle tracks can be distorted by non-negligible amount of material in sensors, read-out electronics, cooling circuits, cables and support structures. In some directions of ID the amount of material exceeds one radiation length [30]. For more accurate reconstruction the information about all material is needed. Complete and up-to-date material description of the ID are available in Geant4 description language [31]. The Geant4 description is slow and therefore unpractical for reconstruction programs.

In order to create a radiation length map for the reconstruction programs probes called geantinos were used on the Geant4 description. Geantinos are hypothetical particles that do not interact with but record the material they transverse. In Paper III a novel and configurable Material Integration Service (MIS) is described which provide material information to the reconstruction programs with a radiation length map in a fast and effective way.

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Figure 4.2: a) The barrel and end cap parts of the Pixel, SCT and TRT are shown. b) A simplified cross-section view of the barrel part of the Inner Detector. The three Pixel barrel layers are closest to the beam pipe. The outermost part is the TRT barrel and in the middle the four barrel SCT layers are shown. As shown, only charged particles are detected by the Inner Tracker (the photon and neutron are undetected). c) Detection points are reconstructed to trajectories.

$^{5}$An event rate of $10^9$ events per second have to be reduced by the trigger (consisting of three different processes, Level1, Level2 and Event Filter) to 100 events per second, that finally will be stored in data bases.
5 Summary of Papers

Paper I
A novel concept for a $\tau$ neutrino appearance experiment is described and results from a first stage of a Monte Carlo simulation are presented. The analysis showed a potential for $\tau$ neutrino detection using RICH technique to observe Cherenkov light from the $\tau$ lepton appearing from charged current interaction of the $\tau$ neutrino with a target nucleon.

Paper II
An earlier proposed $\tau$ neutrino appearance experiment based on a RICH with a liquid radiator ($C_6F_{14}$) was simulated using Geant4 code. This showed that delta electrons, originating from the interaction of the long lived tau decay products with the Cherenkov radiator, gave a severe background by emitting Cherenkov light, making the signal from the tau lepton invisible.

Paper III
A complete and up-to-date information about the material of the detector is needed to make ATLAS' event reconstruction, and thereby also the event selection, more accurate. This note presents a novel Material Integration Service (MIS), providing the material information of the ATLAS Inner Detector from the Geant4 detector descriptions to the reconstruction programs.

Paper IV
Charged Higgs boson production via the gluon-bottom quark mode, $gb \rightarrow tH^{\pm}$, followed by charged Higgs decays into a chargino and a neutralino was studied for a specific choice of the Minimal Supersymmetric Standard Model (MSSM) parameters. In the intermediate MSSM region $4 < \tan\beta < 10$ $H^{\pm}$ decays to SM particles cannot be used for $H^{\pm}$ discovery. It was shown that for an integrated luminosity of 100 fb$^{-1}$ and 300 fb$^{-1}$ charged Higgs decays to non-SM particles can be used to cover the intermediate $\tan\beta$ zone with a 5-$\sigma$ $H^{\pm}$ discovery region.
6 Conclusions and Outlook

In this thesis are presented contributions to the design of two experimental projects which both aim at discovering new phenomena beyond those predicted by the Standard Model (SM) of High Energy Physics. Neutrino oscillations is one such phenomenon, implying that neutrinos are not mass-less as predicted by the basic SM. The existence of charged Higgs bosons is another, implying that there would be not one but two Higgs doublets like in some of the Supersymmetric (SUSY) models.

A new concept previously proposed for the experimental detection of tau-neutrino oscillations, based on the use of Ring Imaging Cherenkov (RICH) detectors in the future CERN Neutrino Beam to Gran Sasso (CNGS), was investigated and evaluated using Monte Carlo simulation techniques. The design of the proposed focusing RICH detector, based on the use of C₆F₁₄ as liquid radiator and of Hybrid Photo Diodes (HPD) as single photon detectors, was optimized to detect the decay of tau leptons produced from interactions of incident tau neutrinos with the liquid. In particular, efforts were made to reduce the background Cherenkov radiation from other particles. The results of the investigation show that the radiation from delta electrons in the liquid is too large to make the detection of the tau leptons possible with the proposed method.

Methods for improving the particle-track reconstruction in the Inner Detector of the ATLAS at LHC, taking into account the scattering in the detector material, were elaborated in the form of a computer service-code. A new concept was introduced by which tracks were generated and followed through the different layers of material in the simulated detector, summing up the integrated effect of particle scattering inside certain volume elements along the track. The integrated effect was parameterized and stored in a look-up table, which could subsequently be used to facilitate a rapid and accurate particle track reconstruction from the track coordinates measured by the detector.

Monte-Carlo simulations were used to evaluate the possibilities to discover the charged Higgs boson by its decays to SUSY particles through analysis of data from the ATLAS detector at LHC. Similar simulation analysis, which had previously been performed for the case of charged Higgs decaying to Standard Model particles, had shown that there is a range of values of approximately 4-10 for the SUSY parameter tan β in which the production rate would be too
small to detect the charged Higgs. The results of the study made here show that charged Higgs can be detected also for such \( \tan \beta \) values if Higgs decays to SUSY particles are used.

The CNGS will start operating in 2006 and the LHC in 2007. There are many indications of that phenomena of some kind beyond the SM will appear in the experiments at LHC, be it manifestations of Supersymmetry or of other hitherto undetected features, like, e.g. large extra dimensions. Using a general-purpose detector like ATLAS at LHC it will be possible to discover - and also perform certain precision measurements of – a wide variety of new phenomena. Later, in the coming decades, when the next generation of linear electron-positron colliders, like the International Linear Collider (ILC) [32] and the Compact Linear Collider (CLIC) [33], are expected to come into operation, further precision studies and also new discoveries will be made possible.

The design, build-up and execution of these new experimental projects will require much dedicated work. It is however likely that the results of the new experiments will radically evolve and improve our present understanding of the fundamental particles and forces in Nature.
7 Swedish Summary, Svensk sammanfattning

Standardmodellen och teorier bortom den

Dagens mest grundligt experimentellt testade teori som beskriver naturens elementära partiklar och de krafter som verkar mellan dem kallas Standardmodellen. Den beskriver hur en grupp av de elementära partiklarna, materiepartiklarna (sex kvarkar och sex leptoner), bygger upp materien och hur en annan grupp partiklar, kraftförmedlarna (fotonen, 8 gluoner och tre vektorbosoner), förmedlar kraftvänkelverkan mellan materieparticklarna. I sin enklaste form förutsäger Standardmodellen att alla partiklar är masslösa. Genom att införa den s.k. Higgsmekanismen, i Standardmodellen får vektorbosonerna, kvarkarna och leptonerna massa. Higgsmekanismen förutsätter existensen av Higgspartikeln, som förblivit den enda partikeln i Standardmodellen som ännu ej är experimentellt funnen. Trots att Standardmodellen med mycket hög precision stämmer överens med experimentella resultat så vet vi att den inte är fullständig eftersom det finns det många teoretiska oklarheter med denna teori.


Syftet med min doktorsavhandling var att utforska karakteristiska särdrag bortom Standardmodellen. Analysstudier av sökandet av den laddade Higgspartikeln var ett av mina projekt. Jag har visat att det är möjligt att detektera de laddade Higgspartiklarna genom att studera deras sönderfall till Supersymmetripartiklar.
LHC — Partikelaccelerator
Arbetet med att studera de laddade Higgspartiklarna utfördes med hjälp av datorsimulering av ATLAS detektorn (A Toroidal LHC ApparatuS), som för närvarande är under uppbryggnad vid Europas gemensamma partikelfysiklaboratorium, CERN, utanför Genève.

Med ATLAS kommer partiklar, som bildas då protoner kolliderar mot protoner i den cirkulära partikelacceleratorn LHC (Large Hadron Collider), att detekteras. LHC placeras i en cirkulär, 27 km lång underjordisk tunnel 100 meter under marken. Då LHC startar år 2007 kommer högenergetiska protoner att kollidera med varandra inne i ATLAS detektorn. Nya partiklar som skapas i kollisionerna kan sedan studeras med detektorn. Om naturens lagar tillåter kommer till exempel de laddade Higgspartiklarna att kunna upptäckas med ATLAS.

För att hitta en ny partikel måste det vara möjligt att kunna rekonstruera kollisionshändelserna i ATLAS med stor noggranhet. Ett projekt jag arbetade med på CERN var att skriva ett program som beräknar hur mycket materiel som sprider en nyskapad partiklar på dess väg bort från kollisionspunkten. Detta gör rekonstruktionen av proton-proton-kollisionshändelserna noggrannare och ökar möjligheterna för ATLAS att påvisa nya partiklar.

CNGS — Neutrinostråle
En annan obesvarad fråga i Standardmodellen är om neutrinerna har massa eller inte. Hälften av Standardmodellens leptoner är neutriner och finns i tre olika neutrinofamiljer, elektronneutriner, muonneutriner och tauneutriner. Om de är massiva tillåts en neutrino av en neutrinofamilj att förvandlas till en neutrino av en annan neutrinofamilj. CNGS (CERN Neutrino Beam to Gran Sasso) är ett projekt som har som mål att utforska neutrinerarnas massegenskaper genom att sända iväg en stråle med muonneutriner från CERN till Gran Sasso i Italien, 732 km längre söderut. Enorma neutrinoledare kommer användas för att försöka detektera tauneutriner i denna stråle. Just nu byggs OPERA (Oscillation Project with Emulsion-tRacking Apparatus) i Gran Sasso, som är en tauneutrinoledare bestående av 1,8 kiloton emulsion och bly.

Ett av mina projekt under min doktorandtid var att undersöka möjligheterna för en ny sorts tauneutrinoledare. Detta nya koncept visades med ett simulations program emellertid vara användbart på grund av en alltför stor bakgrund.
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