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# Phenomenology of Charged Higgs Bosons and $B$ -meson Decays

DAVID ERIKSSON



ACTA  
UNIVERSITATIS  
UPSALIENSIS  
UPPSALA  
2009

ISSN 1651-6214  
ISBN 978-91-554-7422-5  
urn:nbn:se:uu:diva-9564

Dissertation presented at Uppsala University to be publicly examined in Siegbahnsalen, Ångströmlaboratoriet, Lägerhyddsvägen 1, Uppsala, Friday, March 20, 2009 at 13:15 for the degree of Doctor of Philosophy. The examination will be conducted in English.

#### **Abstract**

Eriksson, D. 2009. Phenomenology of Charged Higgs Bosons and  $B$ -meson Decays. Universitetsbiblioteket. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 606. 40 pp. Uppsala. 978-91-554-7422-5.

For more than 30 years the Standard Model has been the theoretical foundation for particle physics. The theory has been verified successfully by experimental tests. Its biggest shortcoming is the non-discovery of the Higgs boson, responsible for giving the other particles masses. Despite its success there are hints that the Standard Model is not the complete theory and many extensions of it, such as supersymmetry, have been proposed.

Extended theories often predict the existence of a charged Higgs boson

and its detection will be a clear sign of physics beyond the Standard Model. The main focus in this thesis is on various phenomenological aspects of the charged Higgs boson. For favorable mass and couplings direct detection is shown to be possible at the Large Hadron Collider in production with an associated  $W$  boson. It is also shown how a light charged Higgs can have measurable effects on spin correlations in decays of pair-produced top quarks. The charged Higgs boson can also be seen indirectly, in for example  $B$ -meson decays, which can be used to put constraints on its mass and fermion couplings. Exclusion limits in two supersymmetric models are given together with a comparison with the discovery potentials for the LHC experiments. A tool for calculating properties, such as masses and decays, of both charged and neutral Higgs bosons in the Two-Higgs-Doublet Model is also presented.

$B$ -meson decays can also be used to test aspects of the strong interaction. Part of this thesis deals with improving and applying phenomenological models to  $B$ -meson decays. Although these models are not derived from first principles, their success shows that they capture important features of non-perturbative strong interactions.

**Keywords:** Supersymmetry, Beyond Standard Model, B-Physics, Charged Higgs Boson, LHC, QCD, Spin Correlations, CMSSM, NUHM

*David Eriksson, Department of Physics and Astronomy, Division of Nuclear and Particle Physics, Box 535, Uppsala University, SE-751 21 Uppsala, Sweden*

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ISSN 1651-6214

ISBN 978-91-554-7422-5

urn:nbn:se:uu:diva-88963 (<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-88963>)

*To my family*



# List of Papers

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

- I D. Eriksson, S. Hesselbach, and J. Rathsmann  
**Associated charged Higgs and  $W$  boson production in the MSSM at the CERN Large Hadron Collider**  
*The European Physical Journal C* 53 (2008) 267-280
- II D. Eriksson  
**PYBBWH: A program for associated charged Higgs and  $W$  boson production**  
*arXiv:0902.0510v1 [hep-ph]* (2009)
- III D. Eriksson, G. Ingelman, J. Rathsmann and O. Stål  
**New angles on top quark decay to a charged Higgs**  
*Journal of High Energy Physics* 01 (2009) 024
- IV D. Eriksson  
**Charged Higgs effects on top spin correlations**  
*In proceedings "Prospects for Charged Higgs Discovery at Colliders"*  
*Proceedings of Science CHARGED2008* (2009) 024
- V D. Eriksson, F. Mahmoudi and O. Stål  
**Charged Higgs bosons in Minimal Supersymmetry: updated constraints and experimental prospects**  
*Journal of High Energy Physics* 11 (2008) 035
- VI D. Eriksson, G. Ingelman and J. Rathsmann  
**Color rearrangements in  $B$ -meson decays**  
*Physical Review D* 79 (2009) 014011
- VII D. Eriksson, J. Rathsmann and O. Stål  
**2HDMC - Two-Higgs-Doublet Model Calculator Physics and Manual**  
*Submitted to Computer Physics Communications*  
*arXiv:0902.0851v1 [hep-ph]*

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# 1. Introduction

Particle physics is the part of physics that deals with the question of what makes up the world on the smallest length scales. It is both an experimental and theoretical science. For the experimental part the smallest scale is the smallest which can be measured, but the theoretical side tries to predict how the world works on even smaller scales. Today the experimental answer to the question is that there are elementary particles, smaller than experimentally measurable, that build up the world. To theoretically describe these particles there is the Standard Model of particle physics. It includes all known particles and also predicts the existence of one more.

The goal of experimental particle physics is to test if the Standard Model is the complete picture, or if there exists new physics, which is physics that can not be described by the Standard Model. To do this experiments must go to higher energies in order to probe smaller length scales and to produce particles which are heavier than the ones predicted by the Standard Model. The main tools are colliders, where particle beams are accelerated to very high energy, corresponding to a speed close to the speed of light, and then brought into head-on collision with each other. The result of a collision like this is the production of various particles which are spread out from the collision point. These particles are detected with a surrounding detector. Some of the particles are not stable and will decay before getting to the detector. From the measurements of the particles in the detector, the experimentalists try to reconstruct what process occurred at the collision point.

There is one high energy collider presently running, that is the Tevatron at Fermilab outside Chicago in the US, and another one in the process of starting up, the Large Hadron Collider (LHC) at CERN in Geneva. The collision energy at the Tevatron, where protons and anti-protons collide, is 1.96 TeV and at the LHC, where protons and protons will collide, the energy will be 14 TeV. At both colliders there are two general purpose detectors that try to detect as many interesting processes as possible within the Standard Model and to discover new physics via processes not predicted by the Standard Model. The Tevatron has not yet discovered any new physics processes but with the higher energy at the LHC new physics might soon be discovered.

On the theory side things are a bit different since there is no major experimental signal that is not explained by the Standard Model. This means that many theories and models for new physics can be constructed as long as they include the Standard Model. Some are more well established and well moti-

vated than others but none of them has been verified experimentally. One such theory is the Minimal Supersymmetric Standard Model (MSSM) which is by many regarded as *the* Model that will supersede the Standard Model.

This thesis is organized as follows. In Chapter 2 the basis of the Standard Model of particle physics is presented together with some important extensions including MSSM. Chapter 3 deals with various experimental issues. This includes experimental tests of the Standard Model and issues related to searches for new physics. Also discussed are how phenomenological models, especially event generators, are needed in experimental physics. Chapter 4 is a summary of the papers included in this thesis. In Chapter 5 some conclusions and an outlook are given. Finally Chapter 6 is a summary in Swedish.

## 2. The Standard Model and some extensions

### 2.1 The Standard Model

Particle physics of today is based on the Standard Model which had its theoretical foundation laid 40 years ago [1]. This theory describes the matter particles that make up all known matter in the universe and most of the forces through which these particles interact. With known matter is here meant the ordinary matter that we see around us and all matter and particles that has been detected in experiments. There are strong indications that the universe is also made up of some extra matter, called dark matter, that is not described by the Standard Model. When it comes to forces the Standard Model only describes three of the four fundamental forces in nature: the electromagnetic, weak and strong forces. Gravity is not a part of the model but there exists attempts to extend the Standard Model to include also gravity, for example string theory [2].

The Standard Model is formulated as a quantum field theory. There are three types of fields, matter fields which describe matter particles, gauge fields which describe force particles, and Higgs fields which are responsible for the generation of mass. The Lagrangian density that defines the theory is gauge invariant, which means that it is invariant under local transformations of the fields. Interaction terms are required by the gauge transformation invariance. The group representation of the transformations, the gauge group, can be Abelian, *i.e.* commuting, or non-Abelian, *i.e.* non-commuting. In the Standard Model both Abelian and non-Abelian gauge groups exist. The different forces have their own terms in the Lagrangian and can be treated separately, but one often writes the electromagnetic and the weak part in a unified manner called electroweak with the gauge group  $SU(2) \times U(1)_Y$ . The gauge group for the strong interaction is  $SU(3)$ .

#### 2.1.1 Particle content

There are three types of particles in the Standard Model, matter particles, force particles and the Higgs boson. Matter particles are, as the names suggests, what make up matter. They come in three families and each family consists of two quarks and two leptons, and their antiparticles. The main difference between the families is that particles in the third family are heavier than their counterpart in the second family which in turn are heavier than their counter-

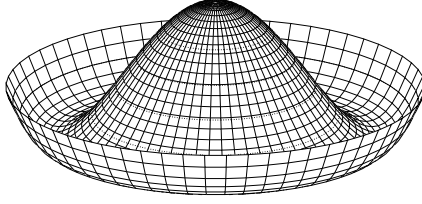


Figure 2.1: A two dimensional representation of the Higgs potential, which has four degrees of freedom. The potential is symmetric in all four dimensions and has a continuous minimum. The process when the Higgs field acquires a vev, *i.e.* when one minimum is chosen, is called spontaneous symmetric breaking.

part in the first family. Ordinary matter is made up of quarks and leptons from the first family. Particles of the two heavier families can only be created in interactions, have a finite life time and decay to particles of the first family. All particles of the three families have been observed in experiments. The last particle to be observed was the top quark [3], which is the heaviest of all known Standard Model particles. The lightest particles are the neutrinos and in the definition of Standard Model used here the neutrinos are exactly massless and only exists as left handed particles.

Force particles are as the name suggests connected to forces. The photon,  $\gamma$ , is the force carrier of the electromagnetic force, the weak force is mediated by the  $Z$  and  $W$  bosons and the gluon,  $g$ , is responsible for the strong force. In the formulation of the Standard Model there exists a fifth boson, the so called Higgs boson or Higgs particle, but it is yet to be discovered. In the Standard Model the Higgs boson is part of the generation of mass via the Higgs mechanism [4] and the Yukawa interactions.

For the theory to be gauge invariant explicit mass terms for fermions and bosons are forbidden. For the bosons the experimental situation is that the photon is indeed massless whereas both the  $W$  and  $Z$  have a mass. In the Standard Model this is solved by the Higgs mechanism. The Higgs field is a complex scalar field  $\Phi(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$  which is a doublet under  $SU(2)$ , *i.e.* it has four degrees of freedom. The potential describing the self-interactions of the Higgs field is

$$\mathcal{V} = \mu^2 |\Phi(x)|^2 + \lambda |\Phi(x)|^4 \quad (2.1)$$

which, if  $\mu^2 < 0$ , has a minimum for non-zero values of the field. As can be seen in Figure 2.1, where a two dimensional representation of the potential is shown, it is not a single minimum, but a continuous one. In nature only one minimum can exist and the mechanism when nature chooses one minimum is called spontaneous symmetry breaking. It is always possible to redefine the Higgs field such that only one of the four components of the field has a

non-zero value at the minimum, a so called vacuum expectation value (vev). This breaks the  $SU(2) \times U(1)_Y$  electroweak symmetry down to the  $U(1)_{em}$  electromagnetic symmetry. The  $U(1)_Y$  and  $U(1)_{em}$  symmetries are not the same and hence the photon will be a mixture of one component from  $SU(2)$  and one from  $U(1)_Y$ . The mixing angle,  $\theta_W$ , is called the Weinberg angle. It also relates the  $W$  and  $Z$  masses since the  $W$  is a pure  $SU(2)$  state whereas the  $Z$  is a mixed state. The gauge interactions for the Higgs field generates, after symmetry breaking, a mass term for the gauge bosons. Of the four degrees of freedom in the Higgs doublet three are used to give mass to the gauge bosons and only one Higgs boson will appear as a physical particle.

To give mass to the fermions a gauge invariant interaction term between fermion fields and the Higgs field called Yukawa interaction is introduced. The mass eigenstates, which are the eigenstates of the Yukawa interactions after spontaneous symmetry breaking, are not the same as the electroweak eigenstates, which are the eigenstates of the unbroken theory. The main consequence of this is that in charged weak interactions the mass eigenstates of the quarks mix. The mixing matrix for the quarks is called Cabibbo-Kobayashi-Maskawa (CKM) matrix [5]. For the leptons, the mixing matrix is diagonal, if neutrinos are massless, and the diagonal nature of the neutral electroweak interactions gives no mixing so in both these cases the mass eigenstates and electroweak eigenstates can be used interchangeably.

In table 2.1 all matter particles and force particles after spontaneous symmetry breaking are shown. Given are their symbol, spin, mass, electric charge and which family they belong to. All massive fermions exist as both left handed and right handed whereas the massless neutrinos are only left handed. Antiparticles exist for most particles but they are not shown in the table.

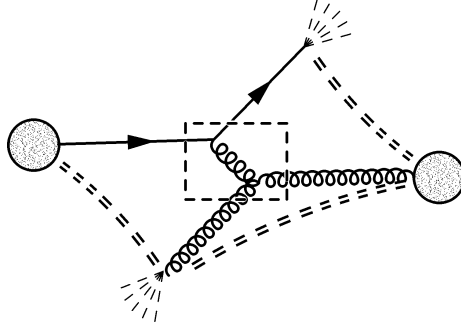
### 2.1.2 Perturbative and non-perturbative

When doing calculations in a quantum field theory one makes a perturbative expansion in a small coupling keeping only the first term, called leading order (LO), or sometimes, when a more accurate calculation is needed, more than one term, giving next-to-leading order (NLO), next-to-next-leading order (NNLO) and so on. In perturbative calculations one sometime encounters infinite integrals. To deal with these infinities different schemes exist to renormalize the theory. One outcome of this renormalization is that the coupling in the original Lagrangian is not the same as the physical coupling and that the coupling to be used in the calculation depends on the energy scale of the process.

In electroweak theory the couplings,  $g$  and  $g'$ , are both small and do not change much with energy. This means that perturbative calculations can be done to high accuracy. The coupling,  $g_s$ , in the strong interaction is on the other hand not that small and in addition it has a strong dependence on the energy. For high energies the coupling is small, the theory is asymptotically

Table 2.1: *Matter particles, quarks and leptons, and force particles, bosons, in the Standard Model after spontaneous symmetry breaking. The quarks and leptons come in three families as indicated. For each particle its symbol, spin, mass and electric charge is given. All masses are from [6] except the top mass which is the most recent value from [7]. For the masses marked with  $^\dagger$  the error is contained in the last digit. All fermions, except the neutrinos, come as both left handed and right handed. Note that antiparticles are not shown.*

Type	Symbol	Spin	Mass (GeV)	Electric charge	Family
Quarks	$d$	$\frac{1}{2}$	$0.0035 - 0.0060$	$-\frac{1}{3}$	I
	$u$	$\frac{1}{2}$	$0.0015 - 0.0033$	$+\frac{2}{3}$	
	$s$	$\frac{1}{2}$	$0.104^{+0.026}_{-0.034}$	$-\frac{1}{3}$	II
	$c$	$\frac{1}{2}$	$1.27^{+0.07}_{-0.11}$	$+\frac{2}{3}$	
	$b$	$\frac{1}{2}$	$4.20^{+0.17}_{-0.07}$	$-\frac{1}{3}$	III
	$t$	$\frac{1}{2}$	$172.4 \pm 1.2$	$+\frac{2}{3}$	
Leptons	$e^-$	$\frac{1}{2}$	$0.00051099891^\dagger$	$-1$	I
	$\nu_e$	$\frac{1}{2}$	$0$	$0$	
	$\mu^-$	$\frac{1}{2}$	$0.105658367^\dagger$	$-1$	II
	$\nu_\mu$	$\frac{1}{2}$	$0$	$0$	
	$\tau^-$	$\frac{1}{2}$	$1.77684 \pm 0.00017$	$-1$	III
	$\nu_\tau$	$\frac{1}{2}$	$0$	$0$	
Bosons	$\gamma$	$1$	$0$	$0$	
	$W^+$	$1$	$80.398 \pm 0.025$	$+1$	
	$Z$	$1$	$91.1876 \pm 0.0021$	$0$	
	$g$	$1$	$0$	$0$	
	$h$	$0$	$?$	$0$	



*Figure 2.2:* Schematic picture of a proton-proton collision where a quark from the left proton is scattered on a gluon from the right proton. Inside the dashed box is the hard, perturbative, process  $qg \rightarrow qg$  and outside different non-perturbative parts. The double dashed lines represent the Lund strings that will fragment into hadrons. The outgoing quark and gluon will be detected as sprays of hadrons, called jets, as indicated at the top and bottom of the picture.

free [8], and perturbative calculations are fine. But as the energy is lowered the coupling grows and gets too big for perturbative calculations to be used. The most interesting phenomena of the strong interactions are those that appear at low energies: formation of hadrons and confinement of quarks and gluons to hadrons. In order to do calculations in this regime one can in some cases use lattice calculations which is a numerical solution to the strong interaction in a discrete space and time. The other possibility is to make use of non-perturbative, phenomenological, models. These models, although inspired by theory, are built with parameters that are fitted to reproduce existing data. A phenomenological model that has been fitted to some data can often then be used to predict the outcome of new experiments and be tested against new data.

### 2.1.3 Partons and hadrons

One non-perturbative feature of the strong interaction is the observation that quarks and gluons, which have a strong charge commonly called color, are always detected bound together into states called hadrons that are color singlets. This is called confinement and makes perturbative calculations of strong processes more complicated since the initial and final states are non-perturbative. The solution is to factorize the problem into a perturbative part and one or more non-perturbative parts, as schematically seen in Figure 2.2. The perturbative part, also called the hard part, has high energy, hence free quarks and

gluons as initial and final states and is calculable with perturbation theory. When one is only interested in the total cross-section  $\sigma$  for a process, which is related to the probability for the process to occur, only the non-perturbative initial state is needed to be mapped to the perturbative one. This is done by using parton density functions, which are parametrizations of the probability to find a parton, quark or gluon, inside a hadron with a certain fraction  $x$  of the hadron momentum and at a specific energy scale  $Q^2$ . The scale dependence of the parton densities are governed by the DGLAP [9] equations. The total cross-section for the process in Figure 2.2 can then be written as

$$\sigma = \int dx_q dx_g f_q(x_q, Q^2) f_g(x_g, Q^2) \hat{\sigma}_{qg \rightarrow qg}, \quad (2.2)$$

where  $f_i(x_i, Q^2)$  are the parton density functions and  $\hat{\sigma}_{qg \rightarrow qg}$  is cross-section for the hard process.

If one is interested in a specific final state a mapping is needed to go from the perturbative final state to a non-perturbative, observable, final state. One way of doing this is to use a similar method as for the initial state and have fragmentation functions that describes the transition of a perturbative parton to a non-perturbative hadron. However, fragmentation functions can not be used to specify the complete final state, only a semi-exclusive state. This is however possible if one uses a hadronization model, such as the Lund string fragmentation model [10]. In this model color triplet strings are stretched between the final state partons as seen in Figure 2.2. As the partons move apart, more and more potential energy is accumulated in the string. It is then energetically favorable to break the string into two pieces by the creation of a quark-antiquark pair. This breaking process is iterated over and over again for all pieces until the invariant mass of the strings are too low and hadrons are instead formed with quark content corresponding to the partons at the string ends.

Another aspect of the strong interaction is the fact that the probability for radiation of a gluon grows as the energy of the radiated gluon decreases. The same is also true for the splitting of a parton into a collinear pair of partons. Experimentally this is seen since high energy hadrons, corresponding to a high energy hard parton, do not appear alone but comes in sprays with many hadrons, called jets, as illustrated in Figure 2.2. In calculations the high probabilities correspond to large logarithms of the energy scale and it is possible to analytically sum these to all orders through a evolution equation similar to DGLAP. Similarly to perturbative calculations this can be done at different orders in the coupling, and the result is called leading log (LL), next-to-leading log (NLL) and so on. Not only the final state partons but also the initial state partons will be accompanied by soft and collinear partons.

It is also possible to convert the evolution equation into an iterative process, called parton shower, where the hard partons in a hard process radiate softer partons before the non-perturbative transition to hadrons. This can be done



as both final state and initial state radiation and in many cases it is a good approximation of the exact higher-order calculations.

## 2.2 Extensions of the Standard Model

Although the Standard Model describes all known particles and most interactions, there are hints of new physics, like neutrino oscillations and dark matter, that are not described by the theory. There are also some theoretical problems, mostly related to the Higgs sector since it contains a scalar particle. One of the problems is the quadratic divergences that appear in the higher order corrections to the Higgs boson mass. When introducing a cut-off where new physics contributions must be included, the higher order terms will get contributions from loops with top quarks,  $W$  and  $Z$  bosons and the Higgs boson itself, which are proportional to the cut-off scale. To keep the Higgs boson mass stable when increasing the scale at which new physics enters requires more and more fine-tuning. Another problem is that of unitarity, which basically is that the probability for scattering processes should be less than unity. This puts an upper bound on the Higgs boson mass around 1 TeV.

There are two main ways to introduce new physics in a theory or model that includes the Standard Model. The first is to start with the Standard Model and extend it with new pieces, like extra fields and particles. The other way is to invent a completely new theory or model in which one includes or embeds the Standard Model as a subpart or as the low energy limit.

### 2.2.1 Two-Higgs-Doublet Models

Since the Higgs boson has not been discovered it is possible that the Standard Model Higgs sector is not complete but can be extended. As discussed above the normal Higgs sector consists of one complex doublet. Adding a second doublet is therefore a simple extension leading to a class of models called Two-Higgs-Doublet Models (2HDMs). In the same way as in the Standard Model, three of the now eight degrees of freedom are used to give mass to the gauge bosons. The remaining five will manifest themselves as three neutral Higgs bosons, two scalar  $h$  and  $H$  and one pseudo-scalar  $A$ , and two charged Higgs bosons,  $H^\pm$ . Both doublets can have components that acquire a vev and contribute to the Yukawa interactions.

In the most general form of 2HDMs both the Higgs self-couplings and the Yukawa couplings can be CP-violating and it is also possible to have flavor changing neutral currents from the Yukawa sector. One, commonly used, way of removing these unwanted couplings is to impose a  $\mathbf{Z}_2$  symmetry on both the Higgs potential and the Yukawa couplings. Under this symmetry the two

doublets transform as

$$\Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow -\Phi_2 \quad \text{or} \quad \Phi_1 \rightarrow -\Phi_1, \quad \Phi_2 \rightarrow \Phi_2, \quad (2.3)$$

*i.e.* they have different parity, and by assigning definite parities to a given fermion its Yukawa mass term can only involve one of the doublets. In this case all couplings will depend on  $\tan\beta$ , which is the ratio between the vevs of the two doublets. Depending on which doublet couples to which type of fermions one gets different models. In the Two-Higgs-Doublet Model Type I only one doublet gives mass to all fermions and in Type II one doublet gives mass to down-type quarks and leptons and the other to up-type quarks.

The 2HDMs does, however, not solve any of the problems in the Standard Model. The Higgs boson masses all have quadratic divergences and unitarity gives bounds on the masses. On the other hand two Higgs doublets with Type II Yukawa couplings are required by supersymmetry as will be discussed below.

### 2.2.2 Supersymmetry

An example of the second way of introducing new physics is Supersymmetry. For a complete introduction see for example [11]. The supersymmetry in these types of theories is a symmetry between fermions and bosons. Each fermion, where each helicity state is treated as a different particle, transforms under the symmetry to its superpartner, which is a boson, and vice versa. Partners to fermions are called sfermions and partners to gauge boson gauginos. In a theory with exact, unbroken, supersymmetry the mass of the particle and its superpartner has to be the same. Supersymmetry also requires that scalar doublets come in pairs with opposite hypercharge so that the Higgs sector of the “Standard Model” part of a supersymmetric theory is a 2HDM. Another consequence of this is that only Type II Yukawa couplings are allowed. The problem with quadratic divergences is solved by the introduction of superpartners since they will introduce new contributions to the Higgs boson masses that exactly cancels the divergences from the Standard Model particles themselves. The cancellation goes further than just quadratic divergences, also logarithmic divergences are canceled. This is taken as a strong motivation why supersymmetry should be realized in nature.

If one wants to build a supersymmetric model which incorporates the Standard Model then the supersymmetry has to be broken since, for example, no boson with the same mass as the electron has been found. It is possible to break supersymmetry only softly, meaning that the quadratic divergences still cancel but logarithmic divergences reappear. There are a couple of different types of terms one can introduce in order to break supersymmetry softly which has the unfortunate consequence of introducing many new parameters. The simplest, and most studied, supersymmetric model which incorporates the

Standard Model is the Minimal Supersymmetric Standard Model (MSSM). Here, the minimum of new particles and couplings compared to the Standard Model has been added.

After breaking of supersymmetry the general MSSM has 124 parameters which makes it hard to do studies with all parameters free. Some of the parameters also induces unwanted physics like tree-level flavor changing neutral currents. In order to reduce the number of parameters one can make assumptions on the breaking mechanism and that some parameters are unified at some high scale. One such model is the constrained MSSM (CMSSM) where gravity is responsible for breaking supersymmetry. CMSSM also has universal scalar masses, universal gaugino masses as well as universal trilinear couplings of the sfermions fields. Besides those three parameters there are two parameters from the Higgs sector.

In CMSSM, and in many other MSSM models, there is a conserved parity, called R-parity, under which all particles are even and all superpartners are odd. One consequence of this is that the lightest supersymmetric particle (LSP) will be stable. The LSP in these models is a good candidate for a dark matter particle if it has only weak interactions. The fact the MSSM can give a dark matter candidate is taken as a further motivation for supersymmetry.

Although supersymmetry does not unify any forces the MSSM gives a hint of unification. The couplings in the Standard Model are very different at the electroweak scale. However, the running of the couplings is such that they get closer together at very high scales but they do not meet all at one point. In MSSM on the other hand the superpartners change the running in such a way that all three couplings unify at  $\sim 10^{16}$  GeV. This is regarded as a strong argument for supersymmetry since an ultimate goal of particle physics theory is to have one unified theory of everything.



## 3. Models and experiments

### 3.1 Tests of the Standard Model

Being the main theory in particle physics for a long time the Standard Model has been tested in many ways. The number of parameters in the theory is 19: 3 in the electroweak sector ( $\alpha_{em}$ ,  $m_Z$ ,  $\sin\theta_W$ ), 9 fermion masses, 3 angles and 1 phase to parametrize the CKM matrix, 1 coupling and 1 phase in the strong sector and 1 Higgs mass. The first basic test is to experimentally find all particles predicted by the theory. As already mentioned all fermions have been found with the top quark being the latest finding. The properties of the fermions, including spin, charge, production and decay modes, are all consistent with the Standard Model. All properties related to the top quark are not yet well measured and some of the measurements can also be consistent with other theories. One example is the measurement of the spin correlation of pair-produced top quarks. The lifetime of the top is so short that it decays before any top hadron is formed. This means that the spin of the quarks will be imprinted in the angular distributions of the decay products. In pair production the top quarks will be produced with their spins correlated and hence the angular distributions of the decay products from the two quarks will be correlated. This correlation has still not been measured.

The situation for the bosons is the same as for the fermions, all basic properties are measured and consistent with the Standard Model, with the exception that the Higgs boson has not yet been found. Extensive searches have been performed, with the experiments at the Large Electron Positron (LEP) collider [12] giving the highest limit of  $m_h > 114.4$  GeV, at 95% confidence level. The non-discovery of the Higgs boson is the biggest experimental shortcoming for the Standard Model.

There are two other important classes of tests, those that test the electroweak sector and those that test the flavor sector. In the electroweak sector there are many observables that have been measured. These include basic properties of the gauge bosons like their masses and both total widths and partial widths. Forward-backward and left-right asymmetries in different production modes at LEP is another set of measurements. For all these observables the 3 electroweak parameters, the Higgs boson mass and the top quark mass are most important in the calculations. It is possible to do fits of these Standard Model parameters using the electroweak measurements. The result of the fits is that the theory is in very good agreement with data. All measurements can be described within the Standard Model. The only problem with the fit is that pre-

ferred mass of the Higgs boson is  $m_h = 77$  GeV [6], which is below the LEP limit. This is not significantly below but one can take this as an indication that the Standard Model Higgs boson can not have a too high mass.

In the flavor sector there are many measurements that try to determine the different angles in the parametrization of the CKM matrix. With these one can test the unitarity of the matrix and so far all measurements are consistent with the Standard Model. Other flavor tests are those that involve rare decays. One of the most important of these is the decay  $b \rightarrow s\gamma$  measured in  $B$ -meson decays. Being a flavor changing neutral current process it is only possible at loop-level in the Standard Model and is therefore more sensitive to new physics. There exists accurate calculations of the pure Standard Model decay, at NNLO [13], which are compatible with the precise experimental measurements [14]. The muon magnetic moment is another flavor sector observable that can be used to test the Standard Model. Here the situation is that there is a deviation of  $\sim 3\sigma$  [6] between the measured value [15] and the calculation [16] which can be taken as a hint for new physics.

## 3.2 Phenomenological models and Monte Carlo

When comparing theoretical calculations and experiments one has to use phenomenological models that describe the low energy strong interactions. Models of this kind normally have one or more free parameters that are not related to the underlying theory. These models can therefore not be used before they have been fitted or tuned to data. Phenomenological models tuned to one set of data can then be used to make calculations and predictions for other measurements and also be tested if compatible with new experiments.

The phenomenological hadronization models are often implemented in Monte Carlo codes that also include perturbative calculations, parton density functions, models for parton showers and other non-perturbative process. These codes are called event generators since they can produce a complete hadronic final state for a given initial state that may involve hadrons. One example is the code PYTHIA [17] which contains the implementation of the Lund string model. Since event generators include many phenomenological models the number of parameters is large, which in turn makes tuning of them difficult and often there exists different tunings where different data has been used. The different models, included in the generator, can also be tested and tuned separately. In PYTHIA one part for which different tunes exists is the multiple interactions and color reconnection part. For some processes it is not clear how the partons should be connected with color strings. There exists different models for this, which often include the possibility that the color is reconnected either randomly or according to some minimization principle. The Soft Color Interaction model (SCI) [18] is one such model. In high energy hadron collisions there is also a possibility that not only one

but multiple hard or semi-hard interactions occurred. In this case it is not even clear how partons from different interactions should be connected with strings in the first place and reconnections can have a large impact on the hadronic final state.

Most of the experimental studies rely on event generators in some way. When planning and building an experiment studies of the physics prospects and expected performance of the experiment are done using event generators together with detector simulation. Once the experiment is up and running the Monte Carlo is used to understand the detector. By using well defined processes the event generator and reconstruction can be tuned so that data and simulation agree. The heavy use of event generators makes them well tested but it can also be a problem when planning a new experiment at a higher energy than before. There is namely no guarantee that the models in the generator extrapolates properly to the new energy.

Although phenomenological models are typically not directly derived from the theory of strong interactions, they can be used to give input on the understanding of non-perturbative strong interactions. If a model gives results that are in agreement with a wide range of data, it has captured some aspect of non-perturbative physics. The basic idea behind the model is then probably correct even though the connection with the underlying theory might be unclear.

### 3.3 Searches for new physics

The first test of a new physics theory or model is to search for the new particles it predicts. So far no experimental evidence for new particles have been found although many searches have been performed. This is strictly not true since in the Standard Model neutrinos are massless but the fact that neutrino oscillations have been observed shows that they in fact have mass, although tiny. It is easy to extend the Standard Model by including an explicit mass term for the neutrinos. This introduces right handed neutrinos which are singlets under all gauge groups, *i.e.* have no interactions except with the Higgs boson. Another observation of new physics is the astrophysical claim [19] that a large part of the mass in the universe is not in the form of Standard Model particles but is some other form of matter, called dark matter. There is still no evidence of what particle or particles that make up the dark matter but the LSP is a prominent candidate.

When searching for a new particle the ultimate goal is to measure the mass and also the couplings for that particle. The outcome of a negative experimental search is to instead set limits on these. A limit on the mass or coupling can only be established in the case when the new physics model is completely specified by the mass or coupling. Otherwise the limit will depend on other model parameters, needed to specify the model used in the anal-

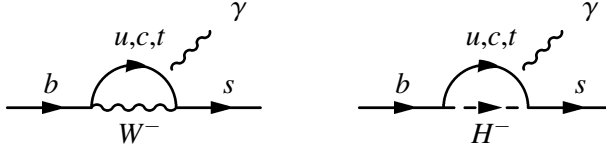


Figure 3.1: Leading order contributions to  $b \rightarrow s \gamma$ . The Standard Model  $W$  contribution is to the left and the 2HDM charged Higgs contribution is to the right.

ysis of the search. One good example is the Higgs boson searches at LEP where not only the Standard Model Higgs was searched for, but also neutral MSSM Higgs bosons [20]. As stated above the limit in the Standard Model is  $m_h > 114.4$  GeV but for the general MSSM no such general limit can be obtained. For certain specific MSSM scenarios, like the  $m_h$ -max scenario and *small- $\alpha_{eff}$*  scenario there are limits,  $m_h > 92.7$  GeV and  $m_h > 87.3$  GeV respectively, but for others, like scenarios with CP-violation, the limits depend strongly on the model parameters and masses down to 0 GeV are allowed. No dedicated study was performed by the LEP experiments for the general 2HDMs, hence there is no generic mass limit on the lightest Higgs boson from a 2HDM. This illustrates one of the problems with searches for new physics, namely that setting general limits on a model with many new parameters is not possible. Searches for particles result in a limit on the search signature which can then be interpreted in one or another model for a specific range of model parameters. In the Higgs boson example this means that to check that a MSSM model, used for example in a theoretical study, is compatible with the LEP searches requires that a reanalysis of all search channels is performed for that specific model.

The second type of new physics tests are indirect tests. These are tests of Standard Model processes where new physics can contribute as new intermediate propagators. One example is the rare decay  $b \rightarrow s \gamma$  which in the Standard Model is mediated by an internal  $W$  boson whereas in the 2HDMs it can also be an internal charged Higgs boson. The leading order contributions are shown in Figure 3.1. All precision tests of the Standard Model can be used to constrain new physics since the new contributions can not be too large and thereby spoil the good agreement between experiments and the Standard Model. For the muon magnetic moment the deviation between experiment and Standard Model calculation can be taken as coming from new physics and then give an estimate on how big the new physics contribution has to be. The hardest indirect constraints come from processes where new physics give contributions at a lower order than, or which are not as suppressed as, the corresponding Standard Model contribution. Flavor changing neutral currents are loop-level processes in the Standard Model whereas there exist many new physics theories and models with tree-level flavor changing neutral currents. Hence the couplings related to the tree-level new physics have strong limits on them.



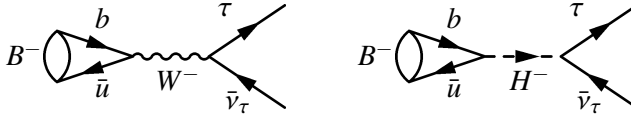


Figure 3.2: Leading order contributions to  $B \rightarrow \tau \nu$ . The Standard Model  $W$  contribution is to the left and the 2HDM charged Higgs contribution is to the right.

Another example is the decay  $B \rightarrow \tau \nu$ , shown in Figure 3.2 which is helicity suppressed when mediated via a Standard Model  $W$ . In 2HDMs the decay can be mediated via a charged Higgs which is not helicity suppressed and depending on the Yukawa couplings the decay can be both enhanced or reduced.



## 4. Summary of papers

### 4.1 Paper I

#### **Associated charged Higgs and $W$ boson production in the MSSM at the CERN Large Hadron Collider**

In this paper we have studied the production of a charged Higgs in association with a  $W$  boson at LHC. A parton level analysis taking only the signal process and the irreducible background into account was performed. In the analysis leptonic decay of  $H^\pm$  and hadronic decay of  $W$  was used. We found detectable signals in standard MSSM scenarios for large  $\tan\beta$  and charged Higgs masses around the top mass.

Further we investigated a special type of MSSM scenarios where the higher order corrections to the Higgs masses give large mass splittings among the heavy Higgs bosons. In these scenarios, this production mode is resonantly enhanced since the production proceeds via an on-shell neutral Higgs boson. The increase in cross-section was found to be up to two orders of magnitude.

The third point studied in the paper was the effect from introducing CP-violating phases in the MSSM scenario. We found however that this gave no measurable asymmetries in the production, both in the standard scenarios and the resonant scenarios.

### 4.2 Paper II

#### **PYBBWH: A program for associated charged Higgs and $W$ boson production**

This paper is a manual for the Monte Carlo code, PYBBWH, developed for paper I. The associated production of  $H^\pm$  and  $W$  is implemented as an external process to PYTHIA. The manual describes how the relevant couplings are set using both standard PYTHIA and via a new common block that allows for the CP-violating case to be studied.

## 4.3 Paper III

### **New angles on top quark decay to a charged Higgs**

Here we have studied spin correlations in top quark decays in the presence of a light charged Higgs boson. Top quarks produced in pairs at colliders have their spin correlated and this correlation will be visible in the angular distributions of the decay products. If a light charged Higgs exists it can mediate top quark decays. The Lorentz structure of the charged Higgs Yukawa couplings can lead to different angular distributions for the decay products as compared to the pure Standard Model case. In the paper we showed that the use of azimuthal angles makes it possible to measure the spin correlations even if the complete event is not reconstructed. We studied the correlations at the LHC both on parton level and also at full hadron level with a simple cut based analysis. Even at hadron level the correlations are visible and possibly they can be used to determine the structure of the Yukawa couplings for the charged Higgs.

## 4.4 Paper IV

### **Charged Higgs effects on top spin correlations**

This is a summary of a talk given at the conference “Prospects for Charged Higgs Discovery at Colliders”. It contains a summary of the work presented in paper III with the focus on the effects from a Two-Higgs-Doublet Model charged Higgs.

## 4.5 Paper V

### **Charged Higgs bosons in Minimal Supersymmetry: updated constraints and experimental prospects**

This paper deals with the charged Higgs bosons in two different MSSM models, constrained MSSM (CMSSM) and non-universal Higgs mass models (NUHM). Both models are based on gravity mediated supersymmetry breaking, has minimal flavor violation and conserved R-parity. In CMSSM all the soft supersymmetry breaking terms of the same type are unified at the GUT scale and in NUHM this unification is not imposed on the mass terms related to the Higgs sector. We performed random scans over a large part of the parameter spaces for these models and checked the model points against both direct and indirect constraints. The direct constraints were various mass limits, like the limit on the lightest Higgs boson mass. For the indirect ones we used several rare decays, like  $b \rightarrow s\gamma$  and  $B \rightarrow \tau\nu_\tau$ , but also the muon magnetic moment and the dark matter abundance. We found that the constraints had the same effects in both type of models. For NUHM we found

that charged Higgs masses down to  $m_{H^\pm} \simeq 135$  GeV survives all constraints for  $\tan\beta \simeq 10$ .

The second part of this work is related to the experimental prospects. We confronted the most recent studies from ATLAS and CMS with the constraints. It turns out that the region where the experiments are most sensitive is to a large extent the same as where the indirect constraints give exclusion.

## 4.6 Paper VI

### Color rearrangements in $B$ -meson decays

In this paper we have developed a model for  $B$ -meson decays based on rearrangements of the color in the partonic final state. This makes it possible to predict decays to both open and hidden charm. The model is based on the leading order perturbative process  $b \rightarrow c\bar{c}s$  and hadronization with the Lund string model. In the final state of the hard process, the  $\bar{c}$  and  $s$  are in a color singlet state and hence connected by a string in the Lund model. In order to have decays to hidden charm, we use the Soft Color Interaction model which rearranges the color connections with a given probability. We have also improved the modeling of hadronization of strings with small invariant masses in order to better describe exclusive branching ratios.

The model contains four free parameters that are fitted against data. For this branching ratio data for both inclusive decays, such as  $B \rightarrow J/\psi X$  with hidden charm and  $B \rightarrow D_s X_c$  with open charm, exclusive decays, *e.g.*  $B \rightarrow J/\psi K^0$ , and the  $J/\psi$  momentum distribution are used. The result is that the model gives a good description of both inclusive and exclusive branching ratios. For the experimental  $J/\psi$  momentum distribution the model also reproduces the data including the tail at low momentum which earlier has been speculated to arise from the production of exotic states.

## 4.7 Paper VII

### 2HDMC - Two-Higgs-Doublet Model Calculator Physics and Manual

We here present the Two-Higgs-Doublet Model calculator 2HDMC. The calculator handles the most general CP-conserving 2HDMs with arbitrary Yukawa couplings. Various parametrizations of the Higgs potential, using different basis for the Higgs fields, can be used. Both the generic basis where both doublets have a vev related by  $\tan\beta$  and the Higgs basis where only one doublet has a vev are included. It is possible to convert between the different parametrizations. All relevant couplings are calculated, *i.e.* self-couplings of Higgs bosons, Higgs-gauge boson couplings and Higgs-fermion couplings. The code gives all two-body, and some three-body, decays of all the Higgs

bosons and can also give the decay  $t \rightarrow H^+ b$ . The model can be checked against constraints from positivity, unitarity and the LEP Higgs boson searches. For the electroweak precision observables  $(S, T, U, V, W, X)$  and  $(g - 2)_\mu$  the contribution coming from the Higgs bosons can be calculated.

The program is written in C++ using object-oriented techniques. It is modular and can be used both as a stand-alone program or as a library. The output when used in stand-alone mode is in the form of plain text or in a LesHouches-inspired format. When used as a library all masses, couplings, decays and observables are accessible through function calls.

## 5. Conclusions and outlook

Although the Standard Model has been around for many years it is still the main theory in particle physics. It describes the known particles and their interactions if one excludes gravity. Precision tests, where precise experimental measurements are compared to detailed theoretical calculations, show that nature can be described by the Standard Model alone. Still there are measurements with large errors where contributions from new physics theories or models can not be excluded. There also exist measurements where a new physics model might give a better description than the Standard Model alone. These measurements can be taken as indications and hints that a new physics model is needed to describe physics at smaller scales and higher energies than what is accessible at experiments today.

Phenomenological models describing different aspects of the strong interaction are needed to compare calculations with experiments. Being a major part in event generators, these models are well tested against existing experiments. When it comes to exact tuning of parameters and details in the implementations there are still uncertainties and room for improvements. With each new experiment probing a different energy regime care has to be taken to ensure that the models are well behaved and that the tunings previously done are still valid. Phenomenological models can by themselves also be used to give understanding and knowledge about the underlying non-perturbative theory.

The discovery of a new particle will be a clear sign that some new physics exists in nature. It will however not be a clear sign of a particular new physics theory or model, but possibly an indication that some models can be excluded. The non-discovery by an experimental search for a new particle has even less exclusion power. Typically a search limit will have to be reinterpreted for each theory or model for an exclusion to be done.

The work presented in this thesis is mostly related to new physics models involving an extended Higgs sector where one extra doublet is added. In general Two-Higgs-Doublet Models, as in paper VII, there is large freedom in the Higgs masses and in the couplings to fermions. In the Minimal Supersymmetric Standard Model there are also two doublets but the masses and couplings are constrained in order to fulfill supersymmetry. The most striking feature of Higgs models with more than one doublet is the appearance of one, or more, charged Higgs bosons. In the Standard Model itself no charged scalars exist and hence finding a charged scalar will be a clear sign of new physics. Whether the charged Higgs will be discovered directly, *e.g.* in associated pro-

duction together with a  $W$  boson as in paper I, indirectly, *e.g.* in top pair spin correlations as presented in paper III, or not all is hard to tell. The indirect constraints, see paper V, indicate that it can be hard for the LHC experiments to directly detect the charged Higgs if an MSSM model of CMSSM or NUHM type is responsible for new physics.

Part of this thesis is not related to new physics but deals with phenomenological models within the Standard Model. Phenomenological models, although well tested, may need to be modified when used in a new context or when tested against new data. In paper VI different models are combined and improved in order to be used to describe  $B$ -meson decays into hidden and open charm.

One goal of the experiments at the Large Hadron Collider is to discover the Higgs boson. If the mass is in a favorable range it will be an easy task and otherwise it will take more time and effort but if there is a Higgs boson with a not too high mass it will probably be discovered. But even after it has been discovered one big question will remain and that is: Is it *the* Standard Model Higgs boson or is it one Higgs boson of many from an extended Higgs sector? If some supersymmetric particles have been found by then, then the answer will be easy: one of at least five Higgs bosons. If the Higgs is the only new particle that is found, no conclusive answer can be given, but it can be taken as a strong indication that there is no more than the Standard Model, at least not at scales probed by the LHC.

Another goal of experimental particle physics is to measure at scales and at energies where the Standard Model can not be used. Theoretical particle physics develops new physics theories and models to predict what the experimentalists will measure. The upcoming physics start of the Large Hadron Collider will hopefully give us the first clear data of a new physics process. If it will be evidence for the Minimal Supersymmetric Standard Model, a Two-Higgs-Doublet Model or something else can only be settled with extensive measurements. As long as some new physics is discovered, it will be possible to start to exclude some of the new physics theories and models but it will also give inspiration to completely new theories. It is also true that whatever is found experimentally, theoretical and phenomenological tools, such as spectrum and model calculators and event generators, will play an important role in the interpretation of the data.



## 6. Summary in Swedish

### Fenomenologi för laddade Higgsbosoner och $B$ -mesonsönderfall

Partikelfysik är den del av fysiken som behandlar frågan om hur världen är uppbyggd på de minsta längdskalorna. Det är både en experimentell och teoretisk vetenskap. För den experimentella grenen är de minsta längdskalorna de minsta som man kan mäta medan den teoretiska grenen försöker beskriva världen på ännu mindre skalor. Det experimentella svaret av idag är att världen är uppbyggd av elementarpartiklar, vilka är mindre än vad som är mätbart idag. Den teori som används för att beskriva dessa partiklar kallas Standardmodellen.

#### 6.1 Standardmodellen

Grunden för Standardmodellen lades för 40 år sedan [1]. Alla kända partiklar beskrivs av teorin som även förutsäger att det finns en ännu upptäckt partikel. Till kända partiklar räknas de partiklar som utgör den vanliga materien som finns i och runt oss och även alla partiklar som skapats och detekterats i olika experiment. Utöver partiklarna själva så beskriver teorin också tre av de krafter med vilka de växelverkar. Det är de elektromagnetiska, svaga och starka krafterna som ingår i Standardmodellen, dock inte gravitation.

Det finns två typer av partiklar, materiepartiklar och kraftpartiklar, vilka även kallas fermioner respektive bosoner. Materiepartiklarna, vilka som namnet antyder bygger upp materia, kan i sin tur delas upp i två kategorier, kvarkar och leptoner. Kvarkar växelverkar med alla tre krafterna och kan med hjälp av den starka kraften binda till mer eller mindre stabila partiklar kallade hadroner. Leptonerna växelverkar bara svagt och elektromagnetiskt. Det går även att gruppera materiepartiklarna i tre familjer där varje partikel i den tredje familjen är tyngre än motsvarande partikel i den andra familjen vilka i sin tur är tyngre än motsvarande partikel i den första familjen. Vanlig materia är uppbyggd av kvarkar, kallade uppkvarkar och nerkvarkar, och leptoner, elektroner och elektronneutriner, vilka kommer från den första familjen. Två uppkvarkar och en nerkvark bildar en proton medan två nerkvarkar och en uppkvark bildar en neutron. Protonerna och neutronerna bygger upp atomkärnor som tillsammans med elektroner bildar atomer.

Kraftpartiklarna är förmedlare av växelverkan. När två materiepartiklar växelverkar med varandra sker det genom ett utbyte av en kraftpartikel. Fotonen är kraftpartikeln för elektromagnetisk växelverkan,  $Z$ - och  $W$ -bosonerna är motsvarande för den svaga växelverkan och gluonen är ansvarig för den starka växelverkan. I tabell 2.1 finns alla Standardmodellpartiklar angivna.

Standardmodellen har under årens lopp blivit testad på många sätt. När det gäller materiepartiklarna och kraftpartiklarna är alla observerade och de uppmätta experimentella egenskaperna stämmer väl med det som teorin förutsäger. Även experiment som har testat växelverkningar visar att det räcker med Standardmodellen för att beskriva det som mäts. Det finns dock indikationer på att Standardmodellen inte är en komplett teori för hur världen är uppbyggd. Viktigast är mätningarna som säger att universum till stor del är uppbyggt av okänd materia, så kallad mörk materia. Dessutom finns det vissa teoretiska problem med Standardmodellen.

## 6.2 Higgsmekanismen och Higgsbosonen

Standardmodellen förutsäger att det finns en partikel som ännu inte är upptäckt, nämligen Higgsbosonen. Higgsbosonen är ansvarig för att de andra partiklarna i Standardmodellen har en massa. I den matematiska beskrivningen av teorin är alla partiklar representerade av så kallade fält. Fysiken som förutsägs av ekvationerna i Standardmodellen är oförändrad om man definierar om fälten enligt vissa regler, teorin sägs ha vissa symmetrier. Om man inkluderar termer i ekvationerna som motsvarar att partiklarna har massa är fysiken inte längre oberoende av omdefinieringar, symmetrin är bruten.

I Standardmodellen används istället Higgsmekanismen för att ge massa åt kraftpartiklarna  $W$  och  $Z$  och för att ge massa åt materiepartiklarna används något som kallas Yukawa-termer. Grunden för dessa båda är Higgsfältet som har den speciella egenskapen att i absolut vakuum, där alla andra partikelfält är noll, kan Higgsfältet vara nollskilt. Det kan ha ett så kallat vakuumförväntansvärde. När man inför ett Higgsfält i ekvationerna för Standardmodellen och ger det ett vakuumförväntansvärde sker det som kallas spontant symmetribrott. En del av symmetrierna i teorin bryts och masstermer för kraftpartiklarna uppträder naturligt. Detta är Higgsmekanismen. Yukawa-termerna är termer i ekvationerna som efter spontant symmetribrott ger masstermer åt materiepartiklarna.

## 6.3 Fysik bortom Standardmodellen

Det finns en mängd teorier och modeller för hur Standardmodellen kan utökas. Gemensamt för dessa är att de förutsäger att det finns nya partiklar. De modeller som ligger till grunden för arbetet i denna avhandling har som gemensam faktor att man adderat ett extra Higgsfält. Dessa, så kallade Två-Higgs-Dublett-Modeller (2HDM), förutsäger att det ska finnas fem Higgs-

bosoner varav två är ett laddat par. En typ av teorier som kräver att det finns två Higgsfält är supersymmetriska teorier. I dessa har en ny symmetri inkluderats vilket leder till en fördubbling av antalet partiklar jämfört med Standardmodellen. Det ger många teoretiska fördelar vilket gör att den, så kallade, Minimala-Supersymmetriska-Standardmodellen (MSSM) är en stark kandidat för att vara den teori som kommer att ta över efter Standardmodellen. Det ”enda” som saknas innan så sker är att upptäcka alla de nya partiklar som MSSM förutsäger.

## 6.4 Acceleratorer och experiment

För att hitta fysik bortom Standardmodellen måste experiment mäta på mindre längdskalor än förut eller försöka skapa partiklar som är tyngre än vad Standardmodellen förutsäger. Detta görs med hjälp av acceleratorer där partiklar accelereras till nästan ljusets hastighet för att sedan krocka med varandra. I krocken skapas en mängd partiklar, genom att rörelseenergi omvandlas till massa, vilka flyger ut från kollisionspunkten. De flesta partiklar som skapas är instabila och sönderfaller till andra lättare partiklar. Runt kollisionspunkten finns en detektor som mäter vilka partiklar som skapats, åt vilka håll de flyger, hur stor massa de har och deras hastighet. Utifrån den informationen försöker man sedan rekonstruera vad som hände i själv kollisionsoögonblicket och vilka instabila partiklar som skapades. Genom att jämföra med analytiska och numeriska beräkningar kan man bekräfta eller utesluta teorier och modeller.

De två acceleratorer med högst energi idag är Tevatronen i USA och LHC vid CERN utanför Genève. Vid Tevatronen upptäcktes 1995 den tyngsta av Standardmodellens materiepartiklar, toppkvarken [3]. Sedan dess har en stor mängd data samlats in men varken Higgsbosonen eller någon annan okänd partikel har upptäckts. LHC, vilket står för Large Hadron Collider, är fortfarande under uppstart. Energin vid LHC kommer att vara ungefär sju gånger större än den vid Tevatronen så förhoppningen är att upptäcka både Higgsbosonen och dessutom några andra nya partiklar, exempelvis de som förutsägs av MSSM.

## 6.5 Sammanfattning av artiklar

Artikel I behandlar produktion av en laddad Higgsboson tillsammans med en  $W$ -boson. Vi undersökte om det är möjligt att observera detta i några olika MSSM-modeller. Resultatet var att för laddade Higgsbosoner med massa ungefär som toppkvarken kan man detektera en signal. För detta arbete skrevs en Monte Carlo-kod vilken är beskriven i artikel II.

I artikel III studerade vi hur en laddad Higgsboson påverkar sönderfall av toppkvarkar. Vid LHC kommer toppkvarkar att produceras i par. Toppkvarken är instabil så i detektorn kommer dess sönderfallsprodukter att mätas. Om den laddade Higgsbosonen är tillräckligt lätt kommer den att påverka de relativa

vinklarna mellan sönderfallsprodukterna från toppkvarkarna. Vi visade att det troligtvis är möjligt att använda dessa vinkelfördelningar för att bestämma den underliggande teorin för sönderfallen. Artikel IV är en sammanfattning av detta arbete vilken presenterades på en konferens.

Artikel V beskriver hur indirekta test och mätningar kan användas för att kunna sätta gränser på den laddade Higgsbosonens massa. Om den laddade Higgsbosonen vore för lätt skulle det påverka till exempel sönderfall av  $B$ -mesoner och andra mätningar. Ingen av de mätningar vi studerade uppvisar några effekter som kan härröra från en lätt laddad Higgsboson vilket ger en gräns på hur lätt den kan vara i de MSSM-modeller som studerades.

I artikel VI har vi studerat fenomenologiska modeller av den starka växelverkan. Modellerna har anpassats och förbättrats för att kunna användas för att beskriva sönderfall av  $B$ -mesoner. Ett fåtal parametrar ingår i modellen. Dessa kan anpassas så att ett stort antal uppmätta sönderfall kan reproduceras.

Artikel VII är en manual för programmet 2HDMC. Programmet är skrivet i C++ och beräknar Higgsbosonernas massor utifrån olika parametriseringar av en generell Två-Higgs-Dubblätt-Modell. Förutom massor beräknar programmet även sönderfall och utför ett antal tester för att se om den specifika modellen uppfyller experimentella gränser.

# Acknowledgments

First I would like to thank my supervisors Johan and Gunnar for all your encouragement and support over the years. You have guided me wisely into the field of particle physics and told me that even though some things take time it will all work out in the end. And so it did. Johan, you always have time for me and my questions and know what to say to get me going again. Gunnar, without your encouragement when I was a undergraduate student I would probably not even have applied for this PhD.

Secondly, I like to thank all PhD students who have been in the group over the years. Nic and Rikard for introducing me to the world of Unix, Linux, Fortran 77 and PYTHIA. Johan for introducing the charged Higgs to our room and bringing the game Puerto Rico to be played over a pizza. It is a pity that we only played two games of War of the Ring. Oscar for all the great work we have done together in our room and discussions on both physics and other topics. Both Johan and Oscar has been great roommates and without you the time at Ångström would not have been as fun as it has been.

I also want to thank the people who have been in the group at one point or another. Our postdocs Stefan and Nazila for the work we done together. Magdalena, Korinna, David, Tim and Lisa, who have as undergraduate students done various projects, have brought energy to the group and made it dynamic.

When it comes to people outside the group my thoughts first go to all PhD students and undergraduate students at the, once department but now, division who have made the lunches in the coffee-room memorable. Some of you have been there as long as I have, some of you not that long, but I will miss you all. Then Ib and Teresa who have helped with computer questions and in keeping the department webserver up and running. Inger and Annica for help with all practical issues during the years.

Finally I like to that thank my family. Mam and dad for your everlasting love and support. Andreas and Sara for being my great brother and sister. The biggest thank goes to Kristina for being the most lovely wife. Without your support and understanding this would not have been possible. A big thank also goes to Teodor and Edvard for coming into my life. You have brought perspective and distraction and will do so for many years to come.



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