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Looking for the Charged Higgs Boson

Simulation Studies for the ATLAS Experiment

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Abstract

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The discovery of a charged Higgs boson ($H^\pm$) would be an unambiguous sign of physics beyond the Standard Model. This thesis describes preparations for the $H^\pm$ search with the ATLAS experiment at the Large Hadron Collider at CERN. The $H^\pm$ discovery potential is evaluated, and tools for $H^\pm$ searches are developed and refined.

The $H^\pm \rightarrow \tau\nu$ decay mode has been known as the most promising $H^\pm$ discovery channel. Within this thesis, first studies of this channel with realistic detector simulation, trigger simulation and consideration of all dominant systematic uncertainties have been performed. Although, as shown by these studies, the discovery sensitivity is significantly degraded compared to studies using a parametrized detector simulation, this channel remains the most powerful ATLAS $H^\pm$ discovery mode. Future searches will rely on multivariate analysis techniques like the Iterative Discriminant Analysis (IDA) method. First studies indicate that a significant sensitivity increase can be achieved compared to studies based on sequential cuts. The largest uncertainty in $H^\pm$ searches is the expected $t\bar{t}$ background contribution. It is shown that numbers obtained from simulated events could be off by a factor of two, decreasing the discovery sensitivity dramatically. In this thesis, the Embedding Method for data-driven background estimation is presented. By replacing the muon signature in $t\bar{t}$ events with a simulated τ , events which allow an estimation of the background contribution at the 10% level are obtained.

The ATLAS τ identification focuses on comparably clean environments like Z and W decays. To optimize the performance in high-multiplicity events like $H^\pm \rightarrow \tau\nu$, tau leptons are studied in $t\bar{t}$ and pile-up events. Variables which do not show discrimination power in high-multiplicity events are identified, and in some cases similar, more powerful variables are found. This allows to recover some of the performance loss and to increase the robustness of the τ identification.

For the analysis of large amounts of data produced by the ATLAS detector, seamless interoperability of the various Grid flavors is required. This thesis introduces translators to overcome differences in the information system between a number of Grid projects, and highlights important areas for future standardization.

Keywords: charged Higgs, tau, ATLAS, HEP, CERN, LHC, Particle Physics, Grid

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List of Papers

This thesis is based on the following papers:

- I B. Mohn, M. Flechl and J. Alwall
ATLAS Discovery Potential for the Charged Higgs Boson in $H^+ \rightarrow \tau\nu$ Decays.
ATL-PHYS-PUB-2007-006 (2007)
- II ATLAS Collaboration
Charged Higgs Boson Searches.
Expected Performance of the ATLAS Experiment: Detector, Trigger and Physics, CERN-OPEN-2008-020 (2008) 1451-1479
- III A. Sopczak, M. Flechl, B. Mohn and T. Ekelöf
An Investigation of the ATLAS Discovery Potential for Charged Higgs Bosons in the Tau Decay Mode Applying an Iterative Discriminant Analysis Method.
ATL-PHYS-INT-2008-002 (2008)
- IV E. Coniavitis and M. Flechl
ATLAS Tau Identification in High-Multiplicity Environments.
ATL-PHYS-INT-2009-106 (2009)
- V C. Isaksson, M. Flechl, N. Möser and M. Schmitz
Embedding Technique for the $t\bar{t}$ Background Estimation in Charged Higgs Boson Searches.
ATL-COM-PHYS-2009-582 (2009)
- VI M. Flechl and L. Field
Grid Interoperability: Joining Grid Information Systems.
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Complementary papers not included in this thesis:

- VII M. Flechl
Search for Charged Higgs Bosons at the LHC.
Proceedings of SUSY07, 458-461 (2007)

- VIII M. Flechl
Charged Higgs Prospects with ATLAS.
PoS(CHARGED2008)006
- IX M. Flechl and B. Mohn, eds.
ATLAS Charged Higgs Boson Searches.
ATL-PHYS-INT-2008-046 (2008)
- X P. Bechtle *et al.*
Identification of hadronic tau decays with ATLAS detector.
ATL-PHYS-INT-2008-003 (2008)
- XI Y. Rozen *et al.*
A Control Sample for $t\bar{t}$ + jets Backgrounds with One or More Leptons in the Final State.
ATL-PHYS-INT-2009-078 (2009)

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Chapter 1

Introduction

“The most exciting phrase to hear in science, the one that heralds new discoveries, is not »Eureka!« (I found it!) but »That’s funny...«”
Isaac Asimov

Particle physics strives to discover and describe elementary particles and their interactions. The current knowledge is summarized in the Standard Model which so far describes all experimental results with high precision. Powerful particle accelerators have been built to challenge this Standard Model, so far without success. The latest in line is the Large Hadron Collider (LHC) at the European Laboratory for Particle Physics (CERN). Recent indications of the incompleteness of the Standard Model fuel the hope of the physicists at the four large LHC experiments to be able to add something conceptually new to our understanding of the building blocks of our universe. Designed as a general-purpose detector, the ATLAS experiment is particularly suited to trace any signs of new physics – be it along the lines of proposed extensions of the Standard Model, or of entirely unexpected nature.

Charged Higgs bosons appear in many extensions of the Standard Model, the most prominent one being Supersymmetry. This thesis describes preparations for the charged Higgs boson search with the ATLAS experiment. The main aspects are the evaluation of the charged Higgs boson discovery potential and the development and refinement of tools for charged Higgs boson searches.

The $H^+ \rightarrow \tau \nu$ decay mode has previously been shown to be the most promising channel for a charged Higgs boson discovery [1]. Within this thesis, first studies of this channel with realistic detector simulation, trigger simulation and consideration of all dominant systematic uncertainties have been performed. The application of consistent assumptions, a common framework and an identical statistical treatment allows the combination of the charged Higgs boson sensitivity in several production and decay modes. Although first-data studies will be based on sequential selection cuts, future searches

will rely heavily on multivariate analysis techniques like the Iterative Discriminant Analysis (IDA) method investigated in this thesis.

The expected top quark pair production background contribution after event selection is the largest uncertainty in charged Higgs boson searches. Numbers obtained from simulated events could be off by a factor of two, leading to a large decrease of the discovery sensitivity. Data-driven background estimation is thus the single-most important item in charged Higgs boson searches. In this thesis, the Embedding Method is presented as a possible solution. It requires the collection of a pure and unbiased top quark pair sample with muons from data. By means of the Embedding Method, the detector response to the muon is replaced by the signature of a simulated tau lepton and the whole event is re-reconstructed. The background contribution can then be evaluated using these events instead of simulated data.

The tau lepton plays an important role in Higgs physics as it is the heaviest known lepton, and Higgs bosons preferably decay to heavy particles. This thesis discusses its most important properties and how they can be used to identify hadronic τ decays with the ATLAS experiment. An efficient and pure identification of hadronic τ decays in charged Higgs boson signal and background events is essential for $H^+ \rightarrow \tau\nu$ searches. However, the ATLAS τ identification usually focuses on comparably clean environments like Z and W decays. To optimize the τ identification performance in high-multiplicity environments like charged Higgs boson events, the likelihood-based τ identification is studied in environments like top quark pair production and pile-up scenarios. The aim is to recover some of the loss in performance compared to Z and W events, and to increase the robustness of the τ identification. This is achieved by removing input variables which do not show discrimination power in high-multiplicity events, or by replacing them with similar but more powerful variables.

Already in 1999 it became evident that a single large computing center located in the CERN areal could not handle the large amounts of data from the LHC experiments cost-efficiently. Instead, computing facilities of the participating institutes are combined to the Worldwide LHC Computing Grid. Different Grid sites can be based on different software. For the processing of the data produced by the ATLAS detector, seamless interoperability of the various Grid projects is required. This thesis describes work carried out to overcome differences in the information system between a number of Grid projects. It focuses on the different techniques and highlights the important areas for future standardization. Translators between different information systems are introduced, and first simple successful cross-grid use cases are presented.

Chapter 2

Theoretical Background

The Standard Model (SM) of particle physics is the theory of the particles currently considered elementary, and their interactions. Together with its potential extensions, it constitutes the theoretical framework of this thesis. The most popular extension, Supersymmetry, is discussed in more detail as it predicts the existence of a charged Higgs boson.

2.1 The Standard Model

2.1.1 The Particle Content

The Standard Model [2, 3, 4] is a highly successful theory, predicting the results of experiments over many orders of magnitude of energy with incredible accuracy. In the formalism of the Standard Model, matter is represented by fermion fields. By introducing local gauge invariance, boson fields emerge as the mediators of interactions.

The physical objects represented by the fields are fundamental point-like particles with properties described by quantum numbers. For every particle, there exists an antiparticle of the same mass and absolute value of the quantum numbers but opposite in sign. One fundamental quantum number is the spin, often visualized as an inner angular momentum although it is in fact a relativistic effect and an intrinsic property of every particle. The spin divides all SM particles into two classes: fermions and bosons.

Fermions have half-integer spin and therefore obey Fermi-Dirac statistics. They can be divided into leptons and quarks. The six leptons are the electron e , the muon μ , the tau lepton τ , and their associated neutrinos ν_e , ν_μ and ν_τ ; the six quarks are called up (u), down (d), strange (s), charm (c), bottom (b), and top (t). Both leptons and quarks are grouped into three generations, each resembling the properties of the other two except for their masses. As was shown by the LEP experiments, there are only three light neutrinos [6]. This

Table 2.1: THE FERMIONS OF THE STANDARD MODEL. *The elementary half-integer-spin particles which constitute matter, their rest mass m in GeV and charge Q in multiples of the elementary charge u are given [5]. The quark masses are central values given in the $\overline{MS}$ scheme. The renormalization scale is 2 GeV for the light quarks and equals their mass for the b and c quark. The top quark mass is measured directly in top decays. The neutrino mass limits are inferred from experiments, stronger limits based on cosmology exist.*

	QUARKS				LEPTONS			
Generation 1	up u		down d		electron e		e neutrino ν_e	
m/GeV Q/u	0.002	$\frac{2}{3}$	0.005	$-\frac{1}{3}$	$5.1 \cdot 10^{-4}$	-1	$< 2 \cdot 10^{-9}$	0
Generation 2	charm c		strange s		muon μ		μ neutrino ν_μ	
m/GeV Q/u	1.27	$\frac{2}{3}$	0.11	$-\frac{1}{3}$	0.106	-1	$< 2 \cdot 10^{-4}$	0
Generation 3	top t		bottom b		tau τ		τ neutrino ν_τ	
m/GeV Q/u	171.3	$\frac{2}{3}$	4.20	$-\frac{1}{3}$	1.777	-1	$< 2 \cdot 10^{-2}$	0

is a strong indication that there are only three generations. The fermions and their most important quantum numbers are listed in Table 2.1.

Table 2.2: THE BOSONS OF THE STANDARD MODEL. *The elementary integer-spin particles which carry the forces, their rest mass m in GeV and charge Q in multiples of the elementary charge u are given [5]. The lower limit for the Higgs boson mass is a combined result of the LEP Experiments [7], the upper limit is a theoretical prediction from the precision measurement of electroweak parameters sensitive to the Higgs boson mass, at a confidence level of 95% [8].*

interaction	particle	m/GeV	Q/u	spin
electroweak	γ (photon)	$0 (< 10^{-18})$	0	1
	$W^\pm$	80.40	± 1	1
	Z	91.19	0	1
strong	g (gluon)	$0 (< 10^{-2})$	0	1
	H (Higgs)	114.4 – 157	0	0

The Standard Model is a gauge theory: its Lagrangian is required to be invariant under a certain set of local gauge transformations. This can only be achieved by introducing gauge fields. They mediate the interactions between the fermion fields and lead to the existence of physical particles, the gauge bosons, listed in Table 2.2. The photon and the W and Z bosons emerge from the combined $SU(2) \times U(1)$ symmetry. They are the messenger particles of

the electroweak interaction, a unified description of electromagnetism and the weak interaction. Similarly, gluons represent the strong interaction following from $SU(3)$ invariance. Photons act on particles carrying a charge, the W and Z bosons on particles with non-zero weak isospin¹, and the gluons on particles carrying a color charge² (quarks and gluons). The fourth known fundamental interaction is gravity which is not described by the Standard Model. For current high-energy physics experiments, gravity is negligible.

The effective range of an interaction depends on the mass of the messenger particle due to the Heisenberg principle of uncertainty³. The range of the massless carrier of the electromagnetic force, the photon, is therefore not limited and has a $\frac{1}{r^2}$ -dependence on the distance of two particles. In contrast, the high mass of the W and Z bosons limits the effective interaction range of the weak interaction to about 10^{-18} m. A typical weak process is the decay of a quark or a lepton.

Like quarks, gluons carry a color charge and thus interact strongly with other gluons. A consequence of this self-interaction is that the energy needed to separate two quarks is proportional to the distance between them. This is the reason why quarks have never been observed in a free state. Instead, they build up colorless (white) hadrons: baryons which consist of three quarks with three different colors (like the proton with two up quarks and one down quark), and mesons with two quarks of opposite color (for example the pion π^+ with one up quark and one anti-down quark). Colorless combinations always carry multiples of the electron charge which explains why fractional charges have never been observed.

The only particle of the Standard Model which has not been observed is the Higgs boson. Its existence would be the consequence of the Higgs mechanism, introduced in the following section.

2.1.2 The Higgs Mechanism

Explicit mass terms in the SM Lagrangian break gauge invariance. However, experiments show that massive particles exist. The most popular way to explain the origin of masses with a gauge-invariant Lagrangian is by introducing a scalar field: The Higgs field, originally proposed by Peter Higgs [9, 10].

The Higgs field is a complex scalar $SU(2)$ doublet $\phi(x)$. Due to gauge invariance and renormalizability requirements, the Higgs potential has the form

$$V_H(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad (2.1)$$

¹Weak isospin is the conserved charge of the weak interaction.

²Color is the conserved charge of the strong interaction, with the possible realizations ‘red’, ‘green’ and ‘blue’.

³Virtual particles with higher masses exist for shorter time periods and thus travel shorter distances.

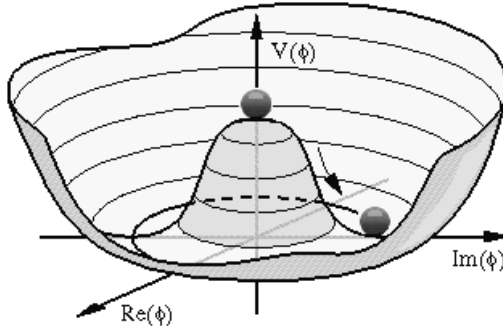


Figure 2.1: HIGGS POTENTIAL. Dependence on two of its degrees of freedom. The vacuum expectation value is non-zero.

with the parameters $\lambda > 0$ and $\mu^2 < 0$. The potential has a continuum of minima (see Figure 2.1). Choosing one of them using the freedom of $SU(2)$ rotations breaks the electroweak symmetry. The conventional choice is the vacuum state

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}. \quad (2.2)$$

When expanding the Higgs field around this state,

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta_2(x) + i\eta_1(x) \\ v + h(x) - i\eta_3(x) \end{pmatrix}, \quad (2.3)$$

the term $h(x)$, corresponding to the physical Higgs boson, appears. The so-called Goldstone fields η can be removed by a suitable gauge transformation. The vacuum expectation value is $v \equiv \sqrt{-\mu^2/\lambda}$. The vacuum state is not $SU(2)$ gauge invariant, although the system (described by the Lagrangian density) is. This is an example of spontaneous symmetry breaking.

When diagonalizing the mass matrix of the resulting Lagrangian, the W and Z mass terms appear, together with the massless photon. The full derivation can be found in Reference [3]. A Yukawa coupling y_i between the Higgs field and the fermions can be introduced in order to give a mass $\frac{1}{\sqrt{2}}y_i v$ to the fermions of the Standard Model.

A Higgs boson lighter than 114.4 GeV has been excluded by the LEP experiments [7]. Precision electroweak measurements exclude a Higgs boson with a mass above 157 GeV, as shown in Figure 2.2. The Higgs boson mass is particularly sensitive to the masses of the W boson and the top quark. A shift in the top quark mass of 3 GeV alters the limits on the Higgs boson mass by about 20 percent.

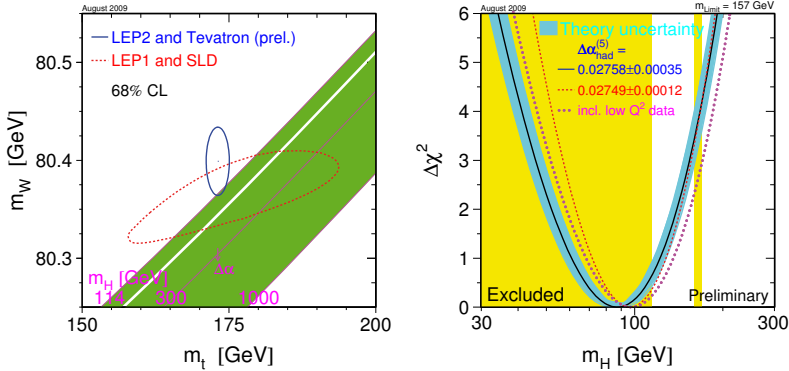


Figure 2.2: LIMITS ON THE HIGGS BOSON MASS FROM ELECTROWEAK PRECISION DATA [8]. Left: The pink lines give the theoretical Higgs mass for given values of the top quark and W boson masses. The values for these masses allowed by experiment is given (blue and red circles). Right: Constraints for the Higgs boson mass from electroweak precision measurements. A light Higgs boson close to the current limit of 114.4 GeV excluded by LEP is favored. A mass higher than 157 GeV is excluded at a one-sided 95% confidence level.

2.2 Beyond the Standard Model

Despite its success, the SM is generally believed not to be a final theory but rather an effective theory valid up to a certain energy. Some of the candidates for a theory beyond the Standard Model are Extra Dimensions [11, 12], Little Higgs models [13, 14], and Technicolor [15]. The most promising extension, Supersymmetry [16, 17, 18, 19], is presented in more detail in the following sections.

2.2.1 Motivation

There are several facts which cannot be derived from the SM (as would be expected from a final theory), and it faces a number of theoretical problems (which could be solved by extending the SM):

- Number of free parameters: There are at least 25 free parameters in the Standard Model. 12 fermion masses, 2 boson masses (one of the boson masses is not a free parameter as soon as the couplings are defined), 3 couplings, 3+3 quark and neutrino mixing angles, and 1+1 CP -violating phase for quarks and neutrinos (which can be zero). If one day quantum gravity is included, at least two more parameters will appear: Newton's constant and a cosmological constant. Although this is not directly a problem, these are more free parameters than generally expected in a final theory.

- Three generations: The Standard Model does not explain why there are three generations of matter particles.
- CP violation: The SM does not explain why the combined charge and parity symmetry is violated in weak decays of some hadrons.
- Dark Matter and Dark Energy: Measurements of the Cosmic Microwave Background suggest that only about 4-5% of the matter in the universe is composed of SM particles (i.e. baryons; neutrinos could make up another few percent). About 23% consists of Dark Matter, and 73% of Dark Energy [20].
- Quantum Gravity: The Standard Model is incomplete in so far as it does not include gravity. This implies that at least at energies of the order of the Planck mass ($m_P \approx 10^{19}$ GeV), gravity cannot be neglected anymore and a new theory is necessary.
- Grand Unification Theories: A unification of the coupling strengths requires the energy-dependent couplings to meet at a certain energy. This is excluded within the Standard Model, but a natural result of supersymmetric models like the MSSM (see Section 2.2.3), as shown in Figure 2.3.

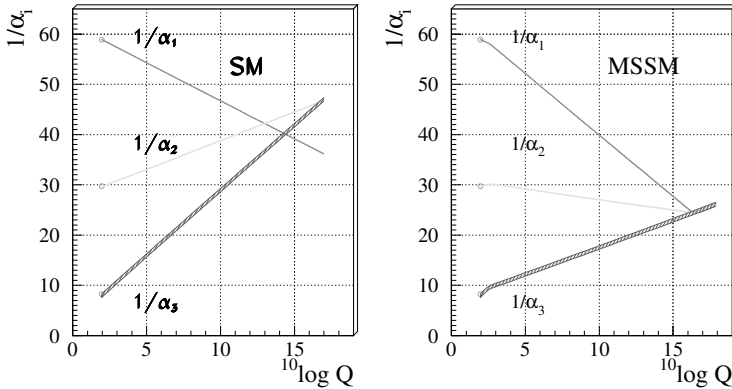


Figure 2.3: THE RUNNING OF THE COUPLINGS. Within the theoretical uncertainties, the couplings of the Minimal Supersymmetric Standard Model meet in one point, as demanded by GUT theories. For the SM, this is clearly not the case [18].

- Hierarchy problem: Quantum mechanics teaches that even in vacuum, virtual particles with arbitrarily high energies are constantly produced via loop diagrams. Higher-order corrections to the mass squared of scalar fields are affected by these loops and are of the order of the cut-off scale of the theory squared (hence called ‘quadratic divergence’), while a Higgs mass m_H of less than 200 GeV is required for electroweak symmetry breaking. This way, the two scales of the theory (electroweak scale and the cut-off scale, e.g. m_P) mix. Within the SM, this can only be explained with an incredible

fine-tuning of the parameters: Depending on the cut-off scale Λ , the bare value of m_H^2 would have to be about 34 orders of magnitude higher than the observable mass and of opposite sign in order to cancel the divergences $\delta m_H^2 = O(\Lambda^2)$, leaving only a physical mass $m_H^2 \approx (100 \text{ GeV})^2$.

2.2.2 Supersymmetry

There are two kinds of symmetries in the Standard Model: External and internal symmetries. Internal symmetries are symmetries in particle space under transformations of the groups mentioned in the previous chapters: the unitary group $U(1)$ and the special unitary groups $SU(2)$ and $SU(3)$, each associated with an interaction. External symmetries are symmetries concerning space-time transformations which are described by the Poincaré group, a generalization of the Lorentz group. After believing for a long time that a non-trivial combination of these groups is impossible [21], the solution was found in the form of Supersymmetry (SUSY). SUSY is an extension of the Poincaré symmetry, and relates boson and fermion fields to each other.

One of the properties of the SUSY algebra is that the square of the four-momentum generator of space-time translations commutes with all the operators mediating Supersymmetry. The masses of the related boson and fermion fields thus have to be equal. This is of course excluded by experiment: supersymmetric particles with SM masses would have been detected a long time ago. If Supersymmetry exists then it cannot be an exact symmetry of nature - it must be broken. There are several models of SUSY breaking. One example is gravity-mediated SUSY breaking in Supergravity (SUGRA) theories: By postulating that Supersymmetry is also a local symmetry, gravity naturally becomes part of the theory.

In order to avoid anomalies, supersymmetric theories require at least two Higgs doublets which leads to five physical Higgs bosons. This consequence is treated in Section 2.3 in more detail.

The phenomenological price for Supersymmetry is high: At least a doubling of the particle spectrum. What are the benefits?

- Solving the hierarchy problem: As bosonic and fermionic loops have opposite signs, the terms for the quantum corrections of the Higgs mass would naturally cancel for exact Supersymmetry or at least be small for softly broken Supersymmetry.
- Grand Unified Theories: In the Minimal Supersymmetric Standard Model (MSSM), all couplings meet at a certain energy – see Figure 2.2.1. This is a prerequisite for every GUT.
- Dark matter: Supersymmetry provides a candidate for dark matter: the lightest supersymmetric particle (provided it is stable, i.e. there is a conservation law which forbids its decay to SM particles).
- Quantum Gravity: Local SUSY automatically contains gravity, but does not yet constitute a full (i.e. renormalizable) quantum theory of gravity.

2.2.3 The Minimal Supersymmetric Standard Model

SUSY is not only a very elegant theoretical concept, it would also provide a rich phenomenology at future colliders. Several SUSY models exist, with the MSSM being most economic in terms of the amount of new particles predicted and the number of free parameters. At tree level and with Supersymmetry as an exact symmetry, no additional free parameters for the SUSY sector would be needed⁴. However, introducing soft SUSY breaking, more than hundred new free parameters appear - the masses of the new particles, phases, mixing parameters, and couplings. Once the SUSY breaking mechanism is fully understood, this number is expected to decrease dramatically.

The SUSY scalars are named after their fermionic SM partners. For each SM fermion, there exist two scalar fermions (sfermions) because the right-handed and the left-handed SM state each have their own superpartner. This leads to an equal number of degrees of freedom. The SM gauge bosons (spin 1) have gaugino (spin 1/2) superpartners, named after the gauge eigenstates of their SM partners plus an 'ino'-suffix: Bino, Wino and gluino. Binos and Winos mix with the Higgsino states, the spin 1/2 superpartners of the Higgs bosons. This leads to four neutral (neutralinos) and two charged mass eigenstates (charginos).

Left-handed and right-handed sfermions mix with a strength proportional to the mass of the corresponding SM fermion. This effect is thus mainly important for the stops, but potentially also for the sbottoms and staus. The gauge and mass eigenstates of the SUSY sector of the MSSM are shown in Table 2.3.

Table 2.3: THE SUSY SECTOR OF THE MSSM. *Mass and gauge eigenstates of the particles are listed [16].*

name	gauge eigenstate				mass eigenstate			
sleptons	$\tilde{e}_L$	$\tilde{e}_R$	$\tilde{\nu}_{e,L}$	$\tilde{\nu}_{e,R}$	$\tilde{e}_L$	$\tilde{e}_R$	$\tilde{\nu}_{e,L}$	$\tilde{\nu}_{e,R}$
	$\tilde{\mu}_L$	$\tilde{\mu}_R$	$\tilde{\nu}_{\mu,L}$	$\tilde{\nu}_{\mu,R}$	$\tilde{\mu}_L$	$\tilde{\mu}_R$	$\tilde{\nu}_{\mu,L}$	$\tilde{\nu}_{\mu,R}$
	$\tilde{\tau}_L$	$\tilde{\tau}_R$	$\tilde{\nu}_{\tau,L}$	$\tilde{\nu}_{\tau,R}$	$\tilde{\tau}_1$	$\tilde{\tau}_2$	$\tilde{\nu}_{\tau,L}$	$\tilde{\nu}_{\tau,R}$
squarks	$\tilde{u}_L$	$\tilde{u}_R$	$\tilde{d}_L$	$\tilde{d}_R$	$\tilde{u}_L$	$\tilde{u}_R$	$\tilde{d}_L$	$\tilde{d}_R$
	$\tilde{s}_L$	$\tilde{s}_R$	$\tilde{c}_L$	$\tilde{c}_R$	$\tilde{s}_L$	$\tilde{s}_R$	$\tilde{c}_L$	$\tilde{c}_R$
	$\tilde{t}_L$	$\tilde{t}_R$	$\tilde{b}_L$	$\tilde{b}_R$	$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_1$	$\tilde{b}_2$
neutralinos	$\tilde{B}$	$\tilde{W}$	$\tilde{H}_u$	$\tilde{H}_d$	$\tilde{\chi}_1$	$\tilde{\chi}_2$	$\tilde{\chi}_3$	$\tilde{\chi}_4$
charginos	$\tilde{W}^+$	$\tilde{W}^-$	$\tilde{H}_u^+$	$\tilde{H}_d^-$	$\tilde{\chi}_1^+$	$\tilde{\chi}_1^-$	$\tilde{\chi}_2^+$	$\tilde{\chi}_2^-$
gluinos	$\tilde{g}$				$\tilde{g}$			

⁴However, as will be explained in the next Section 2.3, additional SM parameters are needed for the (SM-)Higgs sector

2.3 Charged Higgs Boson

Charged Higgs bosons are predicted in many non-minimal Higgs scenarios. The most important examples are Two-Higgs-Doublet Models (2HDM), as ad-hoc extension to the SM as well as in the context of SUSY, and models with Higgs triplets, including Little Higgs models.

2.3.1 Two-Higgs-Doublet Model

The strongest motivation for H^+ searches is that SUSY requires at least two Higgs doublets and thus charged Higgs bosons. There are two reasons for this requirement. In the SM Lagrangian, both the Higgs field H and its conjugate field H^* are needed to give mass to all fermions. This, however, would break the invariance under SUSY transformations which requires the superpotential to be analytic. The second reason is that two doublets are required to cancel contributions to the triangle anomaly which would destroy the renormalizability of the theory.

It is possible to add Higgs singlets and more Higgs doublets to the theory. An example is the Next-to-Minimal Supersymmetric Standard Model (NMSSM), which has an additional Higgs singlet compared to the MSSM. However, models with Higgs triplets or even higher representations generally cannot reproduce the relation between the W and Z mass without fine-tuning.

A Two-Higgs-Doublet Model is favored by (but not limited to) SUSY as it is the minimal necessary extension. The Higgs mechanism works similarly to the case with one scalar doublet in Section 2.1.2 and is only presented schematically here. For a full review, see Reference [22].

The most general type II-2HDM Higgs potential which is gauge invariant, renormalizable, CP invariant, and ensures small flavor changing neutral currents [23] depends on six real parameters λ_i :

$$\begin{aligned}
 V(\phi_1, \phi_2) = & \lambda_1 \left(\phi_1^\dagger \phi_1 - \frac{v_1^2}{2} \right)^2 + \lambda_2 \left(\phi_2^\dagger \phi_2 - \frac{v_2^2}{2} \right)^2 \\
 & + \lambda_3 \left(\left(\phi_1^\dagger \phi_1 - \frac{v_1^2}{2} \right) + \left(\phi_2^\dagger \phi_2 - \frac{v_2^2}{2} \right) \right) + \lambda_4 \left(\phi_1^\dagger \phi_1 \phi_2^\dagger \phi_2 - \phi_1^\dagger \phi_2 \phi_2^\dagger \phi_1 \right) \\
 & + \lambda_5 \left(\Re \left(\phi_1^\dagger \phi_2 \right) - \frac{v_1 v_2}{2} \right)^2 + \lambda_6 \left(\Im \left(\phi_1^\dagger \phi_2 \right) \right)^2
 \end{aligned} \tag{2.4}$$

If all the parameters are non-negative then the minimum of the potential is given by the vacuum expectation values v_1 and v_2 of the two Higgs doublets, $\phi_i^{(0)} = 2^{-1/2}(0, v_i)$, $i = 1, 2$. They are related to each other via the W mass and thus only constitute one new free parameter, usually chosen as $\tan \beta = v_2/v_1$.

Two complex doublets correspond to eight degrees of freedom, three of which give masses to the electroweak gauge bosons just like in the case of

one Higgs doublet. This leaves five physical Higgs bosons: three neutral ones, h^0, H^0, A^0 ; and a charged pair: $H^\pm$.

2.3.2 Constraints in the MSSM

The Higgs potential given in Equation (2.4) together with the MSSM constraints on the parameters yields the following set of relations for the masses at tree level:

$$m_{h^0, H^0}^2 = \frac{1}{2} \left(m_{A^0}^2 + m_{Z^0}^2 \mp \sqrt{(m_{A^0}^2 + m_{Z^0}^2)^2 - 4m_{A^0}^2 m_{Z^0}^2 \cos^2 2\beta} \right) \quad (2.5)$$

$$m_{H^\pm}^2 = m_{A^0}^2 + m_{W^\pm}^2 \quad (2.6)$$

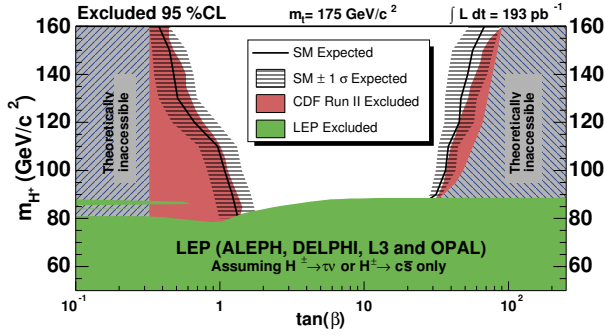


Figure 2.4: DIRECT CHARGED HIGGS BOSON EXCLUSION LIMITS. Results from LEP and Tevatron Experiments [24, 25] for the m_h -max scenario.

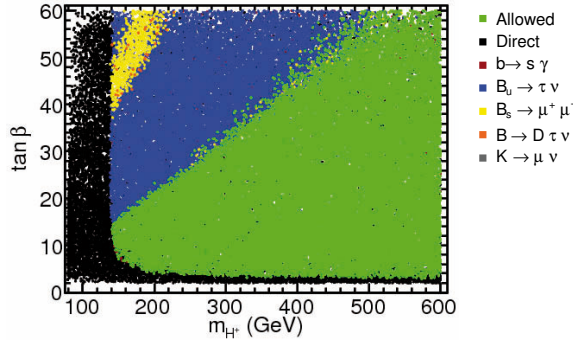


Figure 2.5: INDIRECT CHARGED HIGGS BOSON EXCLUSION LIMITS from B physics and other constraints for Non-Universal Higgs Mass scenarios [26].

At tree level, the Higgs sector of the MSSM depends only on two parameters, usually chosen as $\tan\beta$ and one of the masses of the heavy Higgs bosons,

e.g. m_{H^+} . However, at loop level there are additional contributions from a large number of MSSM parameters. In order to still be able to present results in two-dimensional planes, benchmark scenarios are used. They define all relevant parameters except for $\tan\beta$ and m_{H^+} (or m_A). The most frequently used scenario is called m_h -max [27, 28].

At tree level, the mass of the lightest Higgs boson h^0 is lower than the Z boson mass. Due to large radiative corrections its mass is assumed to be just high enough to have avoided detection at LEP (i.e. larger than 114.4 GeV [7]). The other Higgs bosons are almost degenerate in mass if they are heavier than a few hundred GeV. The lower theoretical limit on the H^0 and $H^\pm$ masses is given by the Z and W boson masses, see Equations (2.5) and (2.6), and is thus similar to the experimental lower limit $m_{H^+} > 79.3$ GeV from the LEP experiments [29]. For very low and very high $\tan\beta$, a charged Higgs boson mass of less than about 160 GeV is excluded by the CDF and D0 experiments [24, 30, 31], see Figure 2.4. Exclusion limits can also be obtained indirectly, for example from observing meson decays which can be mediated by charged Higgs bosons: $B \rightarrow \tau\nu$, $B \rightarrow X_s\gamma$, $B \rightarrow \mu^+\mu^-$, $K \rightarrow \mu\nu$, or by measuring $g-2$, the anomalous magnetic moment of the muon [26]. The current indirect exclusion limits are shown in Figure 2.5. Note that they are very model-dependent. The Equation 2.6 together with the experimental constraint $m_A > 93.4$ GeV [32] translates into another indirect limit: $m_{H^+} > 123$ GeV.

2.3.3 Charged Higgs Boson Production and Decay

For a charged Higgs boson lighter than $m_t - m_b$, the main production mode is

$$gg \rightarrow t\bar{t}, \quad t \rightarrow H^+b \quad (2.7)$$

since the LHC is a top quark factory: about 10^7 top quark pairs will be produced per year. For higher masses, gg and gb fusion are dominant:

$$(2 \rightarrow 3) \quad gg \rightarrow tH^-\bar{b}, \quad (2 \rightarrow 2) \quad gb \rightarrow tH^- \quad (2.8)$$

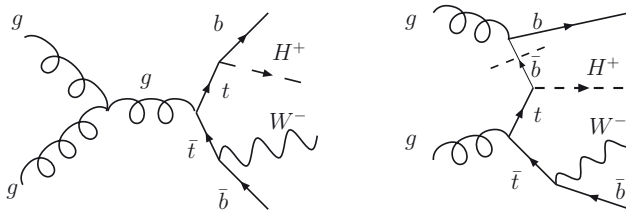


Figure 2.6: CHARGED HIGGS BOSON PRODUCTION MODES. Left: Top quark decays. Right: gg/gb fusion. The $2 \rightarrow 3$ process can be regarded as a higher-order term of the same underlying physics process as the $2 \rightarrow 2$ process

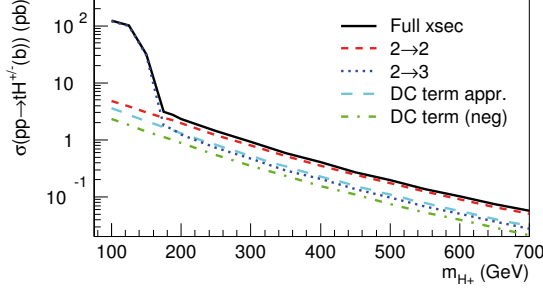


Figure 2.7: CROSS SECTION FOR HEAVY CHARGED HIGGS BOSON PRODUCTION for a center-of-mass energy of 14 TeV and $\tan\beta = 30$. The $2 \rightarrow 2$ and $2 \rightarrow 3$ processes are shown as well as the (negative) double counting term. The $2 \rightarrow 3$ process is approximated by $t\bar{t}$ production and decay for low charged Higgs boson masses [33].

As illustrated in Figure 2.6, these processes describe the same underlying process but in different approximations. Therefore a matching of these two processes is required to avoid overlap [33].

Figure 2.7 shows the cross sections for the different processes. For charged Higgs boson masses below and around the top quark mass, the $2 \rightarrow 3$ process dominates while for higher masses the $2 \rightarrow 2$ process is the major contribution to the total cross section. Heavy H^+ cross sections are known at NLO [34, 35, 36, 37], including the leading supersymmetric corrections.

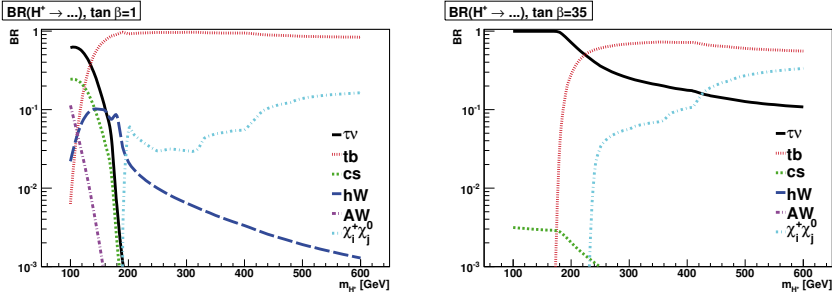


Figure 2.8: CHARGED HIGGS BOSON BRANCHING RATIOS as a function of its mass for two values of $\tan\beta$ in the m_h -max scenario, computed with FeynHiggs 2.6.5 [38, 39, 40, 41].

Light charged Higgs bosons decay almost exclusively to $\tau\nu$ for $\tan\beta > 2$, as shown in Figure 2.8. Above the top quark threshold, decays to tb dominate. The $\tau\nu$ mode is still sizable, in particular for high $\tan\beta$ values. Once kinematically allowed, the branching ratio to sparticles like $\chi^+\chi^0$ becomes comparable to the tb case.

the LHC has seen its first collisions [44] and has been ramping up its center-of-mass energy from 900 GeV at injection towards its design specification of 14 TeV since. Some of the major goals are discovering (or ruling out) the existence of Higgs bosons, Supersymmetry, to investigate CP violation, observe quark-gluon plasma, and to search for exotic scenarios such as technicolor, black holes, leptoquarks, monopoles, axions, and extra dimensions. Additionally, precision measurements of Standard Model parameters will be performed.

Table 3.1: DESIGN PARAMETERS OF THE LHC [45] *The lifetime is the time period during beam collision after which the corresponding quantity is halved. Bunch size values correspond to the RMS of an assumed Gaussian distribution.*

Parameter	Unit	Injection	Collision
Beam Data			
Proton Energy	[GeV]	450	7000
Energy loss per turn per proton	[GeV]	1.2×10^{-10}	6.7×10^{-6}
Proton revolution frequency	[Hz]	11245	
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Circulating beam current	[A]	0.58	
Stored energy per beam	[MJ]	23	362
Interaction			
Events per bunch crossing		-	19
Bunch length $\times$ bunch radius	[mm $\times$ mm]	112×1.2	76×0.3
Bunch radius at IP1	[mm]	0.38	0.017
Bunch spacing	[ns]	25	
Peak luminosity at IP1	[fb $^{-1}$]	-	100
Ring Parameters			
Ring circumference	[m]	26659	
Number of magnets		9594	
Number of main (dipole) bends		1232	
Field of main bends	[T]	0.54	8.33
Power consumption	[MW]	120	
Operating temperature	[K]	1.9	

The most important design parameters are presented in Table 3.1. Most notable are the center-of-mass collision energy of 14 TeV (Tevatron: 1.96 TeV), the spacing between bunch crossings of 25 ns (Tevatron: 396 ns) and the projected about 20 inelastic collisions per bunch crossing (Tevatron: 2). This yields an integrated design luminosity of 100 fb $^{-1}$ per year (Tevatron: ≈ 2 fb $^{-1}$) and implies about 1 billion collisions per second and interaction point.

There are four large experiments at the LHC: ATLAS and CMS, general-purpose detectors; ALICE, to analyze collisions of heavy ions such as lead to study the quark-gluon plasma; and LHCb, to study B mesons to improve our understanding of CP violation.

3.2 ATLAS

The ATLAS detector (see Figure 3.2) [46, 47] is a general-purpose detector. As such, it consists of several subdetectors which record tracks and energy depositions, allowing the identification and measurement of a large class of different particles. The detector has a diameter of 25 m, a length of 46 m and its weight is about 7000 tons. The magnet configuration is based on an inner thin superconducting solenoid surrounding the Inner Detector cavity, and large superconducting toroids with an eight-fold symmetry outside the calorimeters.

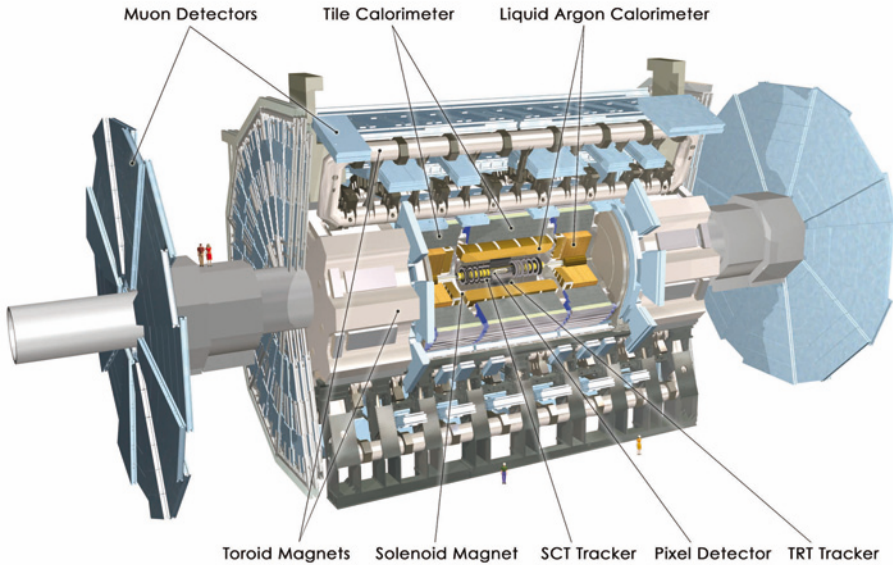


Figure 3.2: ATLAS DETECTOR OVERVIEW [48].

The ATLAS coordinate system is a right-handed system with the x-y plane being transverse to the beam direction. The positive x-axis points from the interaction point towards the center of the LHC, the positive y-axis points upwards. The z-axis follows the beam direction. The azimuthal angle φ increases clockwise around the beam axis when looking into the positive z direction, starting with $\varphi = 0$ on the x-axis. The polar angle θ is the angle with respect to the positive beam axis. Instead of θ , generally the pseudorapidity $\eta = -\ln \tan \frac{\theta}{2}$ is used. R is defined as $R = \sqrt{\eta^2 + \varphi^2}$. The term ‘transverse’

is used for quantities defined in the x-y-plane, like the transverse momentum p_T and the transverse energy E_T .

3.2.1 The Inner Detector (ID)

The Inner Detector [49] consists of three parts, with the innermost semiconductor pixel detector offering the highest granularity. A pixel is a very thin rectangular silicon piece in which the passage of charged particles creates a large number of electrons and holes which are collected by means of an electrical field. The second part is the SemiConductor Tracker (SCT) which consists of semiconducting silicon microstrip using the same principle as the pixel detector. The intersection of two struck strips (each layer consists of two sets of strips with a 40 mrad stereo angle in between) allows a 3D position measurement. The total number of precision layers is limited because of the material they introduce and the high costs. Typically, three pixel layers and eight strip layers (four space points) are crossed by each track. The third component of the ID is the Transition Radiation Tracker (TRT), a straw tube tracker which provides approximately 36 tracking points when charged particles ionize its xenon-based gas mixture. The TRT can detect transition radiation photons and thus improves the electron identification.

The three tracking detectors cover a range of $|\eta| < 2.5$, for the precision tracking with a resolution of 10-20 μm in the x-y-plane (depending on the impact angle) and 50-500 μm in the z-direction, and for the TRT with a resolution in x-y of about 200 μm . Mechanically, SCT and TRT consist of three units: the barrel, extending 1.6 m in the z-direction with cylindrical detector layers around the beam axis, and two identical endcaps of 2.7 m length with detector layers perpendicular to the beam axis. The outer radius of the ID is 1.15 m. The pixel detector is installed together with the beam pipe with the innermost pixel layer being located only 4 cm from the beam line. Because of radiation damage, this layer has to be replaced after a few years of running.

3.2.2 The Electromagnetic Calorimeter (ECAL)

The Electromagnetic Calorimeter [50] consists of a barrel part ($|\eta| < 1.4$) and two end-caps ($1.4 < |\eta| < 3.2$). The barrel is divided into two identical half-barrels, and each end-cap into two rings. The ECAL is a lead-liquid argon (LAr) detector. Electromagnetically interacting particles cause showers in the lead absorber plates and the electrons produced in these showers ionize the liquid argon in the gaps between the plates. Due to the electric field, the charge can be collected and used to derive the energy of the incident particle.

In the central region ($|\eta| < 2.5$), the EM Calorimeter has three cylindrical layers: The first sampling consists of strips providing a precision measurement with a granularity of $\Delta\eta \times \Delta\phi = 0.003 \times 0.1$. The second sampling is the longest in radial direction and consists of square towers of size

$\Delta\eta \times \Delta\phi = 0.025 \times 0.025$. The third and shortest sampling has a granularity of $\Delta\eta \times \Delta\phi = 0.05 \times 0.025$. For $|\eta| > 2.5$, the EM calorimeter consists only of the first two samplings and has a coarser granularity. The region ($1.37 < |\eta| < 1.52$) is not used for precision physics measurement because of the large amount of material of the ID in front of the EM Calorimeter. The signal is sampled every 25 ns. A fit is performed using five samples for each triggered event to reconstruct the energy deposition.

3.2.3 The Hadronic Calorimeter (HCAL)

The hadronic calorimetry consists of three parts: The Tile Calorimeter (TileCal) in $|\eta| < 1.7$, the Hadronic End-Cap Calorimeter (HEC) over the range $1.5 < |\eta| < 3.2$ and the Forward Calorimeter (FCAL) extending to $|\eta| < 4.9$.

The TileCal extends radially from 2.3 m to 4.3 m and consists of the barrel and two extended barrels, with a small gap for cabling in between which is partially filled by the Intermediate Tile Calorimeter. The TileCal is a sampling calorimeter using iron plates as the absorber and tiles of scintillating plastic as the active material. Interaction in the plates transforms the energy of high-energy hadrons such as protons, neutrons, pions and kaons into hadronic showers. When traversing the scintillating tiles, these showers cause light emission which is read out separately on both sides of the tile by a wavelength shifting fibre and a photomultiplier. The TileCal consists of three cylindrical layers with 64 modules each in ϕ . The resulting granularity is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the first two layers, and 0.2×0.1 in the third layer.

The HEC and the FCAL are liquid argon calorimeters. The HEC consists of two independent wheels and works similarly to the LAr EM Calorimeter but uses copper plates instead of lead and a larger liquid argon gap between the plates which makes it more appropriate to the hadronic showering process.

The FCAL is particularly exposed to hard radiation since it extends to about one degree relative to the beam axis. To meet these requirements, a different design is used: In a metal matrix, hollow tubes with metal rods are inserted. The gaps in the tubes are filled with liquid argon. The metal matrix is made of copper (first section) or tungsten (other two sections) [51].

3.2.4 The Muon Spectrometer

The Muon Spectrometer [52] dominates the size of the ATLAS Detector with an outer diameter of 22 m and a length of 46 m. It consists of separate fast trigger and high-precision tracking chambers and is based on the magnetic deflection of muon tracks in the large air-core toroid magnet system. For $|\eta| < 1$, the magnetic bending is provided by the barrel toroid, after a transition region two end-cap magnets cover the range $1.4 < |\eta| < 2.7$. Unlike the situation in the ID, the magnetic field is mostly orthogonal to the muon trajectories.

In the barrel, the high-precision tracking chambers are arranged in three cylindrical layers (called ‘stations’). In the end-cap, the chambers are installed in three vertical stations. For $|\eta| < 2$, Monitored Drift Tubes (MDTs) are used. MDTs are aluminum tubes filled with an argon-carbon dioxide mixture. A high voltage is applied between a central wire and the tube wall, allowing to collect and amplify the electrons produced by the ionizing traversing muon. By measuring the drift time of the electrons, a spatial resolution in the bending direction of the magnetic field of less than 0.1 mm can be achieved. For large pseudorapidities $2.0 < |\eta| < 2.7$, Cathode Strip Chambers (CSCs) are used. They offer a higher granularity and robustness. The CSCs are multiwire proportional chambers with cathode strip read-out. The avalanche around an anode wire from an ionization event induces a charge distribution on the cathodes. A resolution higher than $60\mu\text{m}$ can be achieved.

The much faster muon trigger system covers the range $|\eta| < 2.4$. Apart from triggering, it serves two other purposes: The bunch crossing identification requiring a time resolution better than 25 ns, and the measurement of the so-called ‘second coordinate’ in a direction orthogonal to that measured by the precision chambers, with a typical resolution of 10mm. In the barrel region, three cylindrical stations of Resistive Plate Chambers (RPCs) positioned on the MDT chambers are used. The basic RPC unit is a narrow gas gap filled with tetrafluoroethane ($\text{C}_2\text{H}_2\text{F}_4$) between two resistive parallel plates, separated by insulating spacers. Primary ionization electrons are multiplied into avalanches by an electric field. The signal is read out via capacitive coupling by metal strips. A trigger chamber consists of two such detector layers providing the measurement of two orthogonal coordinates.

The Thin Gap Chambers (TGCs) located near the middle MDT station in the end-cap regions are thin multiwire proportional chambers. A signal in the anode wire caused by electron avalanches in the carbon dioxide-n-pentane gas mixture gives the first coordinate, and a capacitive read-out of the cathode strips orthogonal to the wires provides the second coordinate.

3.2.5 The Trigger System

The ATLAS trigger is based on three levels of online event selection. The Level-1 Trigger [53] is hardware-based and uses input from calorimeter towers and muon trigger chambers to reduce the event rate from 40 MHz to 75 kHz with a latency of less than $2.5\mu\text{s}$. The second and third trigger level are software-based [54]. Level-2 is designed to reduce the trigger rate to 3 kHz by taking advantage of its longer latency (10 ms), allowing the usage of additional detector components (tracking system and precision muon chambers) and the access to the full granularity of the data. The third trigger level reduces the event rate to 100-200 Hz with a decision time of about 1 s which is sufficient to allow access to the full event data and the running of time-costlier algorithms (e.g. advanced track fitting).

Chapter 4

ATLAS Analysis

4.1 Athena: The ATLAS Software Framework

Athena [55] is a software framework representing a concrete implementation of an underlying architecture called Gaudi [56, 57]. This architecture was originally developed by the LHCb collaboration but has become a common project with ATLAS. Athena is the sum of Gaudi and ATLAS-specific enhancements.

Practically, a software framework is a skeleton into which developers plug their code and which provides most of the common functionality and the communication between the different components. For a typical user, Athena is an interface to a set of packages for event production, reconstruction and visualization and to a set of tools which facilitate the writing of analysis algorithms.

An Athena task is configured at run time by conventional Python scripts called JobOptions. Default JobOptions are provided by each package and can be edited to adapt to specific needs before the task is submitted. The python scripts steer the actual code which is usually based on C++ and can directly be used off the central Athena installation. Alternatively, it can be copied to a user-specific area, modified, and recompiled.

4.1.1 Production of Simulated Events

In order to produce events with a realistic detector simulation (called Full Simulation), several steps as illustrated in Figure 4.1 are necessary:

- Event Generation: Modeling of the physics processes that occur in the collisions of two incoming particles in high-energy physics experiments.
- Detector Simulation: Propagation of the particles through the matter of the detector components.
- Digitization: Simulation of the detector response, including the front-end electronics behavior and noise.
- Reconstruction: Rebuilding of the collision event from the raw detector data, e.g. via track fitting and particle identification.

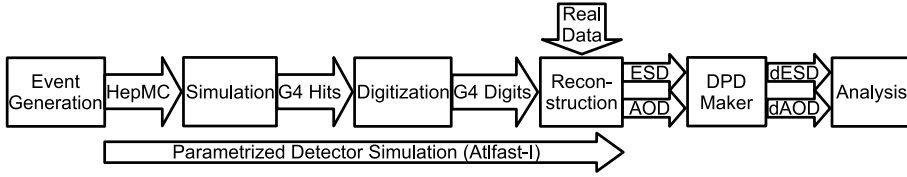


Figure 4.1: ATLAS MONTE CARLO EVENT PRODUCTION. Schematic representation and comparison of realistic to parametrized detector simulation.

4.1.1.1 Event Generation

Event generation consists of modeling the following aspects: The hard process (primary collision); initial and final state radiation; resonance decays (e.g. Z , W); multiple interactions (of other partons from the same protons as the ones which initiated the hard process); beam remnant behavior; fragmentation (of partons to hadrons); and ordinary decays (hadrons, leptons). The general Monte Carlo HEP event generators dealing with all these steps are Pythia [58], HERWIG [59] and SHERPA [60]. Other event generators fulfill a more specialized purpose and need to be interfaced to one of these. For example, MatChig [33, 61], MC@NLO [62] and AlpGen [63]) treat the hard process only, while TAUOLA [64] deals with specific (here, tau lepton) decays. Most of the popular event generators can be used within the Athena framework and configured via JobOption files. If this is not the case then interfaces for externally generated events are provided.

The event generator output contains all vertices of an event, together with the identity and four-momenta of the particles corresponding to each vertex. The event generation step is finished when all short-lived particles have been decayed. The four-momenta of all remaining particles then serve as input to the detector simulation.

4.1.1.2 Detector Simulation

The detector simulation is done using GEANT4 [65], a toolkit for the simulation of the passage of particles through matter. It has been primarily designed for high-energy physics experiments but is now used in all fields where particle interaction with matter is important, for example in space engineering, medical science, and nuclear research.

GEANT4 is highly flexible and allows users to customize all relevant parts of the simulation. The following definitions have to be provided:

- a geometrical model of the detector.
- physical properties (e.g. density, chemical composition) of the materials used.

- properties of the particles appearing in the simulation (e.g. mass, mean life).
- physics models to be used for different energy regimes, and their parameters (e.g. cross sections).

This customization is either done explicitly or by linking to an external library. Within Athena, default values are automatically provided and are sufficient for most detector simulation tasks.

GEANT4 implements all known interactions of particles with matter. Each possesses one or more of the following action types:

- *at rest*, executed after the particle is below an energy threshold set by the user
- *along step*, continuous energy loss or secondary particle production (e.g. Cherenkov radiation)
- *post step*, executed at the end of a step (e.g. secondary particle production via decays or interactions)

The actual simulation starts with GEANT4 pushing all the particles from the event generator output ('primary particles') onto a stack. One particle after the other is then propagated through the detector. Secondary particles created in interactions with matter are also pushed onto the stack (if they are above a user-defined energy threshold). The event simulation is finished when the stack is empty and the last particle has been propagated through the detector.

Each particle moves in discrete steps. All physics processes associated with the particle propose a step length. At the beginning of each step, the mean free path λ for the particle given its energy and the surrounding material is calculated for each potential process. With the definition $n_\lambda = \int_0^\ell d\ell \frac{1}{\lambda(\ell)}$, the probability of traveling a distance ℓ is given by $P(\ell) = e^{-n_\lambda}$.

A random number η , uniformly distributed in the range $(0, 1)$, is generated and using $n_\lambda = -\ln \eta$ the distance to the point of interaction for a certain process is estimated. After repeating this for each possible process, the smallest of the following is chosen for the step length:

- Step lengths proposed by the physics processes
- Distance to the closest geometrical boundary along the trajectory
- Maximum allowed step length set by the user

After the particle has been propagated the chosen step length, the post-step action of the associated process is invoked. If it is an interaction or a decay then the particle is killed and secondaries are generated; otherwise n_λ for each process is decremented by an amount corresponding to the step length and the whole algorithm is repeated for the next step. This procedure continues until the particle is eventually killed in an interaction or a decay, reaches the detector boundaries, or its energy falls below a threshold value specified by the user.

Information about the trajectory is only recorded for the parts of the detector that have been declared sensitive. Typically, these are the detector elements in which information is collected (e.g. dE/dx deposited in silicon sensors or

light produced in scintillators). Different types of interaction like calorimeter-type hits (energy losses) or tracker-type hits (hit positions) are predefined, and this way all the information needed to simulate the detector response later at the digitization step is stored.

4.1.1.3 Digitization

During digitization, the response of the detector and the readout are simulated (including noise) and digit counts for the detector channels are obtained. The input are the hits recorded during detector simulation. The digitization is also performed using GEANT4.

Users have to provide their own GEANT4 implementation of the detector response and readout simulation. This is already part of the Athena framework and changes are only necessary in case a modification of the characteristics of the readout is desired, e.g. in order to investigate ways to optimize the detector. The digitization concludes the actual simulation since its output can be treated in the same way as the detector output from the actual experiment.

4.1.1.4 Reconstruction

The reconstruction [66] is performed in three steps: initialization, stand-alone reconstruction and combined reconstruction. During initialization, digits from the GEANT4 output or from collision data are read, the ATLAS geometry is built, the magnetic field map is loaded, and calibration and alignment constants are retrieved.

In the stand-alone reconstruction, information for each subdetector is reconstructed separately. For the calorimeters, matrices containing the energies of the cells are filled and with this information jets are built, the missing transverse energy is computed and electron/photon identification is performed using shower-shape variables. Muon tracks are reconstructed in the Muon Spectrometer and extrapolated to the interaction point. Different algorithms search for charged particle tracks in the Inner Detector, either over the full range or over ‘seeds’ found by other detectors (jets, electrons, photons, muons).

During the last step, the information from several detectors is combined. Muons reconstructed in the Muon Spectrometer are refined by matching the track to an Inner Detector track, muons with low transverse momenta are found by matching Tile Calorimeter cells to an Inner Detector track. The primary vertex is reconstructed using all the tracks in the event. Pairs of Inner Detector tracks are formed in order to detect photon conversions and K_S^0 decays. Photons with high transverse momenta are identified by requiring certain values for variables describing the shower shape in the Electromagnetic Calorimeter and the absence of a track in the Inner Detector. For the identification of electrons with high transverse momenta, a track reconstructed in the Inner Detector with transition-radiation hits in the TRT is required, to-

gether with a cluster in the Electromagnetic Calorimeter showing an energy deposition compatible with the momentum measured for the track in the Inner Detector. Hadronically decaying tau leptons are identified from narrow jets in the calorimeters together with a small number of charged tracks in the Inner Detector. Jets are b -tagged by reconstructing the displacement of the B meson decay vertex in the Inner Detector and the identification of soft electrons or muons using Inner Detector, Calorimeter and Muon Spectrometer information.

The reconstruction output is available in two formats: As Event Summary Data (ESD) or as Analysis Object Data (AOD). ESDs contain all the detector-level information like calorimeter cell depositions and track hits, as well as information at the object level (e.g. jets or leptons). The AODs only contain the objects plus detector-level information in the vicinity of these objects.

4.1.2 Parametrized Detector Simulation

Atlfast-I [67] replaces the ATLAS detector simulation, digitization and reconstruction by only one step in which the event generator output is smeared with efficiencies, misidentification rates and resolutions measured in studies with a realistic detector simulation. It runs within Athena and can thus use all event generator interfaces provided. The Atlfast-I output are AODs with format and content similar to the AODs obtained after reconstructing the full simulation output. Of course Atlfast cannot replace the more accurate full simulation, but it can give approximate estimates of signal and background rates. This is particularly useful if a) high accuracy is not required, b) the object of the study is comparably easy to model (like a lepton final state), or c) the number of events needed is very high. Atlfast-I is typically four to five orders of magnitude faster than full simulation. For typical studies of QCD dijet backgrounds, the number of events required is of the order of 10^{10} . Assuming a CPU time of 15 minutes per event, this would take about 300000 CPU years using full simulation.

Atlfast starts with the list of particles from the event generator output. Values are assigned to calorimeter cells depending on the detector resolution, and calorimeter clusters are built. For electrons and photons in the particle list, the associated clusters are identified. The remaining clusters are then used for jet reconstruction. Muons are treated separately. Atlfast additionally provides a list of reconstructed charged tracks and can simulate the efficiencies and rejection rates for the tagging of b jets, light jets and τ jets.

A lot of effort has gone into determining the correct parametrization of the resolutions used for the smearing in order to obtain results matching full simulation. It has been shown [67] that Atlfast can be used for a great variety of studies in which details of the detector performance (like non-Gaussian tails or cracks) are not crucial.

Recently, Atlfast-II [68] has been introduced. The main difference to Atlfast-I is that it parametrizes the shower shape of particles in the calorimeter (FastCaloSim) and that it offers a parametrized simulation of the tracking (Fatras). It is possible to run it as a hybrid between realistic and parametrized detector simulation. The most common use case is full simulation of the Inner Detector and the Muon Spectrometer, and parametrized simulation of the calorimeter. This configuration can provide GEANT4 Hits as output and thus the ordinary digitization and reconstruction can be used, allowing e.g. the simulation of the trigger which is run in the digitization step. Depending on the amount of full simulation used, Atlfast-II is about 1-2 orders of magnitude faster than full simulation.

4.1.3 Analysis

The reconstruction output (ESD, AOD) can only be read within the Athena framework. A physics analysis can be set up in two ways: Either as a package within the Athena framework; or by using Athena tools to produce a flat ntuple, i.e. files which can be processed in a stand-alone ROOT [69] session, without Athena.

In the current ATLAS computing model, derived ESDs and AODs (dESD, dAOD) are provided by the central production system and are the starting point of every analysis. They are group-specific and are produced from ESDs and AODs via

- Skimming: keeping only events of interest for the particular study.
- Thinning: for each event, keeping only interesting objects.
- Slimming: for each object, keeping only interesting information.

The analyses can run directly on these Athena-based formats, or on further derived formats.

4.2 Tau Identification

The τ is an exceptional particle in the lepton sector of the SM: it is the only lepton with a mean free path small enough to decay within the boundaries of a typical high-energy physics detector, and it is the heaviest lepton. The latter has important consequences as Higgs bosons normally couple to mass, and tau leptons are thus more likely to appear in a Higgs boson decay than any other lepton. Examples are the decay of a neutral Higgs boson to two tau leptons both in the SM and the MSSM, and the decay of a charged Higgs boson to a tau lepton and a neutrino. In SUSY models, staus often play a crucial role, and tau leptons also appear in their decays. Additionally, tau leptons are used in SM precision measurements [6].

4.2.1 Tau Lepton

The mean life of a τ is $2.9 \cdot 10^{-13}$ s which means that it typically travels a few millimeter (depending on its relativistic γ , e.g. 3 mm for $E_\tau = 50$ GeV). Most of the time, it decays before reaching the innermost layer of the ATLAS detector and only its decay products are observed. The τ mass is 1.777 GeV [5], making it more than 15 times heavier than the muon and more than 300 times heavier than the electron.

Table 4.1: TAU LEPTON DECAY MODES. $h^\pm$ signifies a $\pi^\pm$ or $K^\pm$ meson, and n a π^0 meson or a photon [5]. Charge conjugate modes are implicitly included.

Type	Decay mode	Branching ratio
one prong leptonic	$e^- \bar{\nu}_e \nu_\tau$	17.4%
	$\mu^- \bar{\nu}_\mu \nu_\tau$	17.9%
one prong hadronic	$h^- \nu_\tau$	11.6%
	$h^- \nu_\tau \geq 1n$	37.1%
three prong	$h^- h^- h^+ \nu_\tau$	9.8%
	$h^- h^- h^+ \nu_\tau \geq 1n$	5.4%
five prong	$h^- h^- h^- h^+ h^+ \nu_\tau \geq 0n$	0.1%

The tau lepton decay modes and branching ratios are given in Table 4.1. The τ decays to a lepton 35% of the time. The only difference between such decays and prompt electrons or muons is their impact parameter, as a secondary vertex cannot be reconstructed from a single charged track. The impact parameter value is often within the uncertainties of its experimental determination and it is thus typically not possible to tell if a detected lepton has been produced in a τ decay.

The focus of τ identification is thus on hadronic decays, the remaining 65%. Among those, about three quarters lead to one charged track, and one quarter to three charged tracks. Other decay modes are negligible in comparison. τ decays can be further distinguished by the number of neutral particles produced.

4.2.2 Hadronic Tau Reconstruction and Identification

Due to their large cross section, the main background for τ identification in hadron colliders are jets initiated by quarks and gluons (in the following, simply called “QCD jets” as opposed to “ τ jets”). Electrons are also frequently misidentified as τ jets because of characteristics similar to 1-prong τ decays: one charged track, and significant energy deposition in the calorimeter.

τ jets have a lower track multiplicity (1 or 3) than QCD jets, and they are more collimated. This leads to a narrow shower in the calorimeter. Compared to QCD jets, τ jets have a much larger electromagnetic component since their π^0 content is on average higher. This is particularly important for 1-prong τ decays where the branching ratio to π^0 states is large. Another difference is that the invariant mass of a τ jet is on average smaller than for a QCD jet.

These characteristics are used for distinguishing τ jets and QCD jets with ATLAS [70, 71]. Technically, the first step is the τ reconstruction in which candidate τ jets are built. This is followed by the τ identification in which discriminating variables are used to suppress the QCD jet (and potentially electron) background.

The τ reconstruction is performed by two complementary algorithms, using different seeds: a high-quality track with transverse momentum above 6 GeV, or a topological cluster in the calorimeter with transverse energy above 10 GeV. Each seeded object is considered a τ candidate. τ jets can be seeded by both algorithms – this is the case for 70% of all candidates in $Z \rightarrow \tau\tau$ events. 25% are only calorimeter-seeded, and 5% only track-seeded. For all candidates, basic properties are calculated: the position in η and ϕ , the energy, and the associated track multiplicity. Additionally, several discriminating quantities are calculated to be used by the algorithms in the following step.

A number of τ identification methods are used within ATLAS: a simple cut-based method, mostly aimed at early data; and multivariate methods based on neural networks, probability density range searches, or boosted decision trees. The default method is the tau Log-Likelihood ratio (tauLLH) which is briefly described in the following.

The tauLLH is based on 16 input variables, listed in Table 4.2. From each of these, individual probability density functions (PDFs) are constructed for τ jets and QCD jets depending on the number of tracks associated to the τ candidate (single- or multi-prong), the number of associated π^0 clusters (zero or at least one), and p_T (ten ranges). The PDFs are extracted from simulated events (see examples given in Figure 4.2). The prongness and the seed type define which input variables are used to calculate the discriminant for a certain τ candidate.

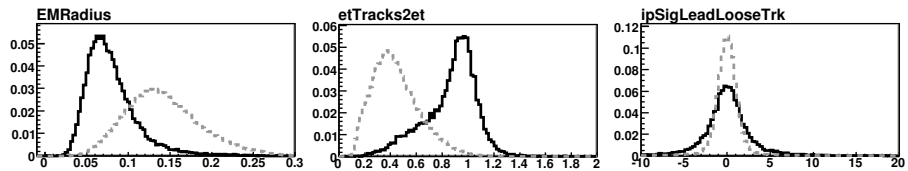


Figure 4.2: TAU LLH PDFs. Three of the PDFs used as input for the tauLLH are shown for 3-prong candidates with $30 < p_T [\text{GeV}] < 45$. Solid: τ . Dashed: QCD jet

Table 4.2: INPUT VARIABLES TO THE TAU_{LLH}. 1p or 3p means that the variable is used for 1- or 3-prong candidates. The last column indicates if the variable is only used for calorimeter-seeded (c) or track-seeded (t) candidates, or in both cases (b).

Name	Explanation	1p	3p	a
EMRadius	E_T -weighted radius of depositions in EM calorimeter cells	X	X	c
isolFrac	ratio of E_T deposition: $E_T(0.1 < \Delta R < 0.2)/E_T(\Delta R < 0.4)$	X	X	c
stripWidth2	E_T -weighted width of the energy deposition in the strips	X	X	c
nStrip	number of strip hits with $E > 200$ MeV within $\Delta R < 0.4$	X	X	c
etHad2etTracks	hadronic calorimeter E_T divided by Σp_T of the tracks	X	X	c
etEM2etTracks	EM calorimeter E_T divided by Σp_T of the tracks	X	X	c
etTracks2et	Σp_T of the tracks divided by the calorimeter E_T deposition	X	X	b
dRmin	ΔR between tau candidate and closest associated track		X	b
dRmax	ΔR between tau candidate and most distant associated track		X	b
trkWidth2	width of the tracks weighted with their momenta		X	t
massTrkSys	invariant mass of the system of associated tracks		X	t
nIsolTrk	number of tracks in the isolation cone $0.2 < \Delta R < 0.4$	X	X	t
MVisEflow	invariant mass from tracks and calorimeter depositions	X	X	t
ipZ0sin θ SigLeadTrk	longitudinal impact parameter significance of leading track	X		t
ipSigLeadLooseTrk	transverse impact parameter significance of leading track	X	X	c
trFlightPathSig	significance of the signed transverse flight path		X	t

The unnormalized logarithm of a likelihood ratio is defined as $LLH = \ln \frac{L_T}{L_J}$, where L_T and L_J stand for the likelihood that a candidate is a τ jet or a QCD jet, respectively. Neglecting correlation terms, the likelihood can be written as a product of the PDFs:

$$L_k = \prod_{i=1}^{nVar} p_i^k(x_i), \quad k = T, J \quad (4.1)$$

$p_i^k(x_i)$ is the (signal or background) PDF for the input variable x_i , and $nVar$ the number of input variables. Due to the logarithm in its definition, the total LLH can now be written as a sum over the LLH values of the individual input variables:

$$LLH = \sum_{i=1}^{nVar} \ln \frac{p_i^T(x_i)}{p_i^J(x_i)}. \quad (4.2)$$

LLH is the discriminant of the tau_{LLH} method. Typical distributions for the τ and QCD jet case are shown in Figure 4.3 (left). The optimal LLH cut value differs from analysis to analysis, depending on how tight the τ selection should be. Different cut values lead to different working points on the τ efficiency versus QCD jet rejection curve, as shown in Figure 4.3 (right). In many studies, an efficiency of about 30% is required, leading to a QCD jet rejection rate of the order of 1000.

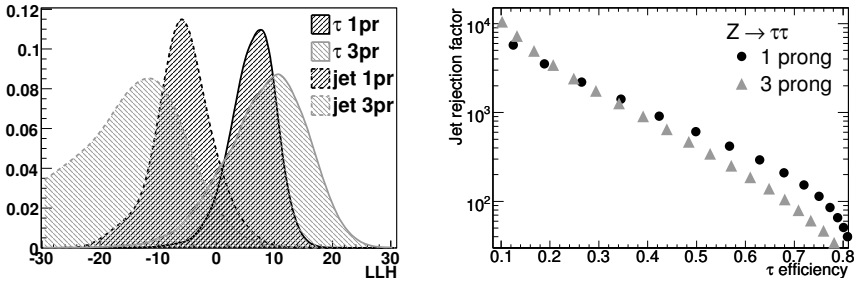


Figure 4.3: TAU LLH PERFORMANCE. The τ source are $Z \rightarrow \tau\tau$ events, and the jets are from QCD dijet events. Left: tauLLH discriminant distribution. Right: τ efficiency versus QCD jet rejection. Both distributions depend strongly on the type of events investigated.

Chapter 5

The Grid

Grid computing is a form of distributed parallel computing characterized by combining resources from *multiple administrative domains* with a *common security mechanism*. This distinguishes it from conventional parallel computing models: a computing center with a homogeneous set of resources, employing a batch system and a storage system. The Grid allows the combination of computing resources like CPUs and storage elements irrespective of type and distance, including the possibility to unite computing centers into one large system. Ideally, the user should experience it as one homogeneous supercomputer in spite of its relative internal heterogeneity and loose coupling between its various sites. The eponymous Grid paradigm is to ultimately make access to computing resources as easy as to the electric power grid [72].

The Grid concept was originally designed by Foster and Kesselmann [72]. They define the Grid as “coordinated resource sharing and problem solving in dynamic, multi-institutional virtual organizations” [73]. A Virtual Organization (VO) is a set of individuals who collaborate to achieve a common goal. The rules of sharing computing power, storage space, software and data are defined in terms of these VOs. An example is the ATLAS VO whose members have e.g. access to a certain quota of CPU time and to ATLAS data – but not to CMS data.

Secure and coordinated access to the distributed resources requires a particular software layer which is called middleware because it sits in the middle of the operating system and the application software. It consists of a series of cooperating programs, protocols and agents and is ideally transparent to the user. Typical middleware components are:

- Information System: collects and distributes information about the available resources. Basic tasks are service discovery, service selection, service monitoring and accounting.
- Services for job management: tools and a user interface for job submission and monitoring, and a solution for sharing the workload across the Grid.

- Data management: file transfer, input data caching, and indexing of output data.
- Security infrastructure: encryption, authentication and authorization.

5.1 The LHC Computing Grid

When the design process for the LHC Computing Grid (LCG) [74] started in 1999, it rapidly became clear that a single large computing center located at CERN could not process the large amount of data produced at the LHC experiments in a cost-efficient way. In 2001, the CERN council thus approved the LCG project with the mandate to develop, build and maintain a *distributed* computing infrastructure for the storage and analysis of data from the LHC experiments [75]. In the following years a memorandum of understanding was developed, defining the Worldwide LCG Collaboration (WLCG). The members of the WLCG are CERN and institutes all over the world which provide resources for processing and storage of LHC data. Today, more than 170 computing centers in 34 countries are participating, with about 100000 CPUs at their disposal.

The WLCG consists of three layers called tiers. The Tier-0 is located at CERN. From the approximately 300 GB/s of data produced by the LHC experiments, the entire stream of 300 MB/s of triggered events passes through the Tier-0. From there it is sent via private fiber optic cable links to the 11 Tier-1 centers: ASGC (Taiwan), BNL and Fermilab (USA), GridPP (UK), IN2P3 (France), INFN (Italy), KIT (Germany), NDGF (Nordic countries), NIKHEF/SARA (Netherlands), PIC (Spain), and TRIUMF (Canada). These sites process the raw data, provide storage and analysis facilities, and distribute data to about 160 Tier-2 institutes, typically via the national research and education networks, or the public internet. The main purpose of the Tier-2 is to provide capacity for end-user analyses and event simulation. Outside of the scope of the WLCG are the Tier-3 facilities — local resources like a small university cluster or even individual PCs which are used to access data and analysis facilities. The exact implementation of the tier model varies between the different LHC experiments, and is described in the respective Computing Technical Design Reports [55, 76, 77, 78].

5.2 Nordic Datagrid

The Nordic DataGrid Facility (NDGF) [79] manages the Nordic LCG Tier-1 in a collaboration of Denmark, Finland, Norway, and Sweden. It is unique among the Tier-1s in so far as it is a distributed Tier-1 (and not a single computing center), and that it leverages existing resources instead of owning them [80]: the resources are under the control of different national organiza-

tions such as SweGrid [81]. Three out of the four LHC experiments are among the NDGF clients: ALICE, ATLAS, and CMS.

The origin of NDGF is a small distributed testbed set up by the NorduGrid Collaboration [82] which showed the need for a much larger facility. Today, NDGF is mostly operations-oriented and provides services, while the NorduGrid Collaboration is development-oriented and provides the middleware used by NDGF: ARC, the Advanced Resource Connector [83].

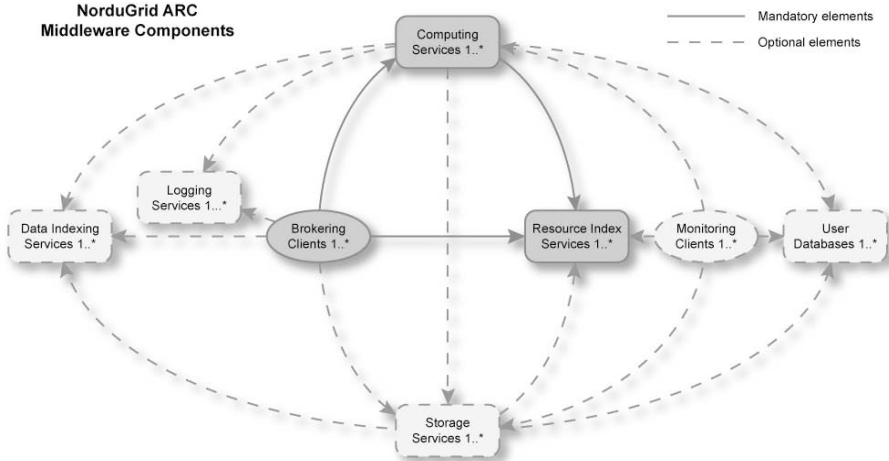


Figure 5.1: COMPONENTS OF THE ARC ARCHITECTURE. Arrows point from components that initiate communications towards queried servers [83].

Like most Grid middleware, ARC is based on the Globus Toolkit [84]. Globus is not a deployment-ready solution but rather an open-source software bundle for building Grid middleware. The ARC-specific enhancements are guided by the distributed nature of the NDGF Tier-1 which implies inhomogeneous site policies, operating systems, storage elements, and batch systems. ARC is lightweight and has only three mandatory components, illustrated in Figure 5.1: The computing service (manages jobs and moves data), the information system, and the brokering client (discovers resources and decides to which Grid site a job is sent). Optional components include data storage and indexing services, and monitoring tools.

The most important differences in terms of interoperability between ARC and other Grid middleware used in the WLCG can be found in the job submission and the information system components. Unlike the model implemented by gLite [85] (the middleware dominantly used in the WLCG), the ARC resource brokering is done on the client side and job submission thus proceeds directly from the user interface to the computing resources and not via an intermediate instance (called Resource Broker). The information system used by different WLCG middleware solutions can differ in three ways: the protocol used to access the information, the format in which the information is

stored, and the schema which defines the information a particular type of resource has to provide. Information system interoperability is a prerequisite for efficient usage of all potential resources independently of the middleware solutions used at Grid sites: jobs can only be pushed to adequate resources if their existence and properties are known.

Chapter 6

Summary of Papers

Paper I

The ATLAS discovery potential for hadronic τ decays of a heavy charged Higgs boson, $H^+ \rightarrow \tau\nu$, was studied. A new matched production algorithm for the processes $gg \rightarrow tbH^+$ and $gb \rightarrow tH^+$ allowed a consistent investigation of the mass range from $m_{H^+} \approx m_t$ up to 600 GeV. This was the first ATLAS charged Higgs boson study based on a realistic signal simulation of the ATLAS detector. For the background, a parametrized simulation was used. A greater variety of background channels than in previous studies was investigated, showing the need for new selection cuts with additional discriminating power. Such cuts were introduced. The study showed that with three years of ATLAS data in low luminosity runs, an H^+ can be discovered for m_{H^+} up to around 160 GeV, and that the sensitivity region extends to charged Higgs boson masses of several hundred GeV for high values of $\tan\beta$.

Paper II

In this paper, the ATLAS H^+ sensitivity was studied in five different final states. The author of this thesis performed the studies on the heavy H^+ decays to $\tau\nu$, and was as co-convenor of the ATLAS H^+ group additionally responsible for the coordination of the efforts in the other H^+ decay channels, and for editing the chapter on charged Higgs boson searches. The study aimed both at a refinement of existing ATLAS H^+ analyses, and introducing new H^+ channels into the ATLAS portfolio. The work presented the first ATLAS H^+ studies consistently performed with a realistic detector simulation including all three trigger levels and taking into account all dominant systematic uncertainties. The charged Higgs boson mass region of 90-600 GeV was investigated. For the first time, the sensitivity of all H^+ channels was combined. It was shown that the ATLAS experiment is capable of detecting the charged Higgs boson in a significant fraction of the $(\tan\beta, m_{H^+})$ parameter space with

its first 10 fb^{-1} of data. The region around $\tan\beta = 7$ is experimentally hard to reach, but exclusion sensitivity is given also in this area.

Paper III

This study constituted the first attempt of improving the ATLAS H^+ sensitivity with a multivariate method which considers input variable correlations in the final discriminant. The Iterative Discriminant Analysis (IDA) method was used and results were compared to a method based on sequential cuts. On a purely statistical level, a significant improvement was observed. However, a rigorous study of the systematic uncertainties of the method is still necessary in order to draw any definite conclusions.

Paper IV

The τ identification in two high-multiplicity environments, pile-up and $t\bar{t}$ events, was studied. Several ways of improving the performance and robustness of the tau likelihood method were investigated. The usage of dedicated probability density functions instead of the default ones (based mostly on W and Z events) was shown to have only a small effect. Removing variables redundant in the investigated environments and introducing new variables to replace them leads to an increased rejection rate of jets (typically 25-50%) in spite of using a lower number of input variables than in the default likelihood.

Paper V

Top quark pair production with tau leptons is the dominant background for most charged Higgs boson searches. This study investigated the possibility of emulating this channel in preparation for data-driven background estimation. The emulation is done by replacing tracks and calorimeter cells associated to a muon in a $t\bar{t} \rightarrow b\mu\nu bW$ sample collected from data with the signature of a simulated tau lepton. It was shown that most relevant distributions can be reproduced within a 10% level.

Paper VI

Data from the LHC experiments is reconstructed and analyzed on the LHC Computing Grid. The fact that different flavors of Grid-enabling software are used on the various Grid sites decreases the efficiency in which Grid resources can be used. In this study, the interoperability of different information systems, which are used to find Grid resources, was improved using translators. Additionally, important areas for future standardization were identified.

Chapter 7

Conclusions

The work described in this thesis is part of the preparations for the charged Higgs boson search with ATLAS. As the current Standard Model does not contain any charged scalar particle, the discovery of a charged Higgs boson would be a definite sign of a more general theory. Candidate theories range from ad-hoc extensions which simply add an additional Higgs doublet, to concepts like Supersymmetry and Little Higgs which try to overcome some of the shortcomings of the SM.

Like any other analysis, charged Higgs boson studies with ATLAS data will be performed using the Grid. To be able to use any Grid site irrespectively of the job submission client requires seamless interoperability of the different Grid projects united in the LCG. Paper VI shows that it is possible to translate between the information systems of the major projects, a prerequisite for interoperability. In practice, the standardization of the Grid information model is necessary to achieve this goal.

As the heaviest lepton, the τ plays a crucial role in charged Higgs boson searches. $H^+ \rightarrow \tau\nu$ is the primary decay mode over a sizable region of the MSSM parameter space, and stays the most promising discovery channel even when $H^+ \rightarrow tb$ becomes dominant. However, the identification of a hadronic τ in an active event such as $t\bar{t} \rightarrow bH^+bqq$ is more challenging than in the type of events the τ identification is usually optimized for: W and Z decays in collisions at low instantaneous luminosity. Paper IV investigates the τ identification performance in high-multiplicity environments such as $t\bar{t}$, and in the presence of pile-up. It is shown that training the algorithm on this type of events only leads to marginal improvements. However, several currently used input variables do not improve the τ identification performance in the environments studied. Their removal does not only increase the robustness (and decrease the susceptibility to systematic uncertainties) but even leads to a significant performance increase for 3-prong τ decays. Several new variables have been identified which can replace some of the currently used ones. An

increase in QCD jet rejection of more than 50% can be achieved in spite of using fewer variables than in the default τ identification.

Paper II shows that the background contribution from $t\bar{t}$ events after event selection is the largest uncertainty in charged Higgs boson searches. This uncertainty reduces the H^+ sensitivity dramatically and calls for a method for data-driven background estimation. Paper V proposes the Embedding Method which requires the collection of a pure and unbiased $t\bar{t}$ sample with muons from data. The Embedding Method removes the signature of the muon and embeds the detector response to a simulated tau lepton in the tracking system and the calorimeter. The whole embedded event is then re-reconstructed and the background contribution can be evaluated using these events instead of simulated data. The technical implementation has been adapted to $t\bar{t}$ events and the performance has been tested. It is shown that (provided a pure $t\bar{t}$ sample with muons can be selected) the total systematic uncertainty of the $t\bar{t}$ background can be reduced from previous 30-50% down to about 10%. Important future steps include the preparations for selecting such a pure sample, and testing the embedded events (including impurities) in the context of the actual analysis.

The main part of this thesis deals directly with optimizing the selection of charged Higgs bosons, and evaluating the discovery sensitivity (Papers I-III). In Paper I, the first ATLAS H^+ study with a realistic detector simulation is carried out. A slight degradation of the H^+ discovery potential with respect to previous studies using a parametrized detector simulation is observed, but by identifying new discriminating variables some of the sensitivity loss could be recovered. The work towards a more realistic sensitivity evaluation has been continued in Paper II by including a trigger simulation and evaluating all dominant systematic uncertainties. For the first time, the combined reach of the five most important H^+ channels has been evaluated. A light H^+ can be discovered for $\tan\beta$ below 4 and above 20 for a mass up to 150 GeV. As statistical uncertainties dominate these results, there is some hope that the region around $\tan\beta \approx 8$ can eventually be filled. A charged Higgs boson exclusion up to almost $m_{H^+} = m_t$ is feasible. The sensitivity for a heavy charged Higgs boson depends strongly on its mass. Discovery reach is given for $\tan\beta > 28$ around $m_{H^+} = 200$ GeV, and $\tan\beta > 58$ for $m_{H^+} = 350$ GeV. H^+ exclusion is possible up to a mass of $m_{H^+} = 600$ GeV and $\tan\beta = 55$.

The LHC has seen its first collisions in November 2009 and is on track to start collecting high-energy collision data in 2010. The ATLAS experiment has the potential to discover the H^+ with about a year of high-quality data, or to start improving the current H^+ limits even earlier. The most important future tasks related to H^+ studies are the rigorous testing of the Embedding Method, studies of the QCD jet background using data, and the optimization of the trigger strategy.

Kapitel 8

Summary in Swedish

Inom partikelfysik studerar man materiens minsta beståndsdelar (elementarpartiklar) och de krafter som verkar mellan dem (växelverkningar). Detta beskrivs av en teori som kallas för Standardmodellen.

Standardmodellen. Vi känner till tolv typer av partiklar som materia byggs upp av. De kallas fermioner och delas in i sex leptoner och sex kvarkar. Mest känd bland leptonerna är elektronen. Det finns ytterligare två leptoner som liknar elektronen men som är tyngre: myonen och tauonen. De har en kort livstid och sönderfaller till lättare partiklar. Dessa tre leptoner är elektriskt laddade och de har varsin elektriskt neutral partner, de så kallade neutrinerna. Neutrinerna har väldigt små massor i förhållande till övriga partiklar. Av de sex kvarkarna är uppkvarken och nerkvarken viktigast, eftersom de är de byggstenar som neutroner och protoner består av. Kvarkarna är också laddade, men till skillnad från leptonerna binds de alltid ihop till sammansatta partiklar som kallas hadroner (till exempel protoner och neutroner). De resterande fyra kvarkarna kallas sär-, charm-, botten- och toppkvarken, och de bygger bara upp instabila hadroner som sönderfaller snabbt.

Krafterna som verkar mellan fermionerna förmedlas av partiklar som kallas bosoner. Två partiklar växelverkar med varandra via utbyte av en boson. Standardmodellen beskriver tre av de fyra kända växelverkningarna: den elektromagnetiska växelverkan, som binder ihop elektronerna med atomkärnan och som förmedlas av fotoner; den svaga växelverkan, som styr en typ av radioaktivt sönderfall och som förmedlas av W och Z bosoner; och den starka växelverkan, som binder ihop neutroner och protoner i atomkärnan och som förmedlas av gluoner. Den fjärde växelverkan, gravitationen, har man inte lyckats beskriva med Standardmodellen.

Det finns en boson till: higgsbosonen. Det är den enda partikeln vars existens Standardmodellen förutsäger som ännu inte har upptäckts. Higgsbosonen är ansvarig för att de andra partiklarna har massa.

Mycket tyder på att Standardmodellen inte är en fullständig teori, men det finns många teorier om hur den kan utökas till att beskriva det som saknas. En

populär utökning är Supersymmetri. Den förutsäger att alla kända partiklar har en hittills okänd partnerpartikel, och att det finns fem higgsbosoner istället för en. Två av dessa är laddade, H^+ och H^- , och de är huvudpersonerna i denna avhandling.

LHC och ATLAS. Den hittills upptäckta higgsbosonen och supersymmetrin är troligtvis de största anledningarna till att LHC (Large Hadron Collider, svenska: stor hadronkolliderare), den största maskinen i mänsklighetens historia, konstruerades. Den installerades i en 27 km lång cirkulär tunnel vid CERN-laboratoriet nära Geneve. Där kommer två protonstrålar att accelereras och styras så att de kolliderar vid speciella punkter där man har byggt stora detektorer för att analysera vad som händer vid kollisionerna.

En av detektorerna vid LHC är ATLAS. Den är 46 m lång, 25 m hög och väger 7000 ton. ATLAS består av ett antal subdetektorer som registrerar spårren av partiklarna som skapas i kollisionerna och mäter deras energi. När man kombinerar informationen från de olika subdetektorerna är det möjligt att identifiera partiklarna.

Informationen som LHC producerar är 700 MB/s, vilket motsvarar en CD per sekund! Det är omöjligt att spara och analysera all denna information på CERNs datorer. Därför använder man ett stort internationellt nätverk av datorer som kallas för LHC Computing Grid. Idag består detta nätverk av mer än 170 beräkningscentra med omkring 100 000 CPUs. Data som produceras av detektorerna skickas till elva så kallade Tier-1-centra. Nordic DataGrid Facility, som är ett nordiskt samarbete, är ett av dessa Tier-1-centra. De mjukvaror som används av deltagande beräkningscentra kan vara väldigt olika. Det är ett viktigt mål att de kommunicerar med varandra så att man kan skicka data och beräkningar från ett centrum till ett annat.

Sammanfattning av artiklarna. Artiklarna I-III undersöker möjligheten att upptäcka den laddade higgsbosonen vid ATLAS med hjälp av simulerade händelser. De visar att när man byter till en mer realistisk beskrivning av kollisioner och osäkerheter i analysen så är det svårare att detektera laddade higgsbosoner än man tidigare trott. Trots det så är potentialen ändå större än vid andra partikelkolliderare. Det finns anledning att tro att det blir lättare att hitta bosonen med hjälp av multivariata metoder.

Artiklarna IV- V beskriver utvecklingen av hjälpmedlen som används till att söka efter laddade higgsbosoner. Artikel IV visar hur man kan förbättra identifikationen av tauoner (som bl.a. kan produceras i sönderfall av laddade higgsbosoner) i händelser med många andra partiklar. För att registrera signalen av laddade higgsbosoner måste man först förstå bakgrunden till signalen mycket exakt. En metod för att undersöka bakgrunden beskrivs i Artikel V.

Artikel VI undersöker hur kommunikationen mellan gridcentra som inte använder samma mjukvara kan förbättras. För detta arbete skrevs en kod som översätter information som olika gridcentra publicerar och som söks av andra gridcentra. I artikeln påpekas även områden där standardisering kan förbättra situationen i framtiden.

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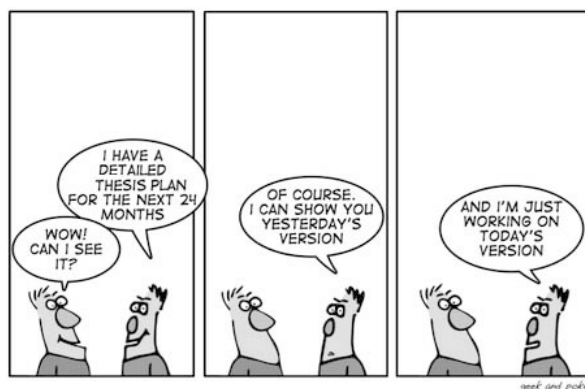


Figure 8.1: A PIECE OF ADVICE TO THE FUTURE PHD GENERATION: Discipline and careful planning are the keys to a successful doctoral thesis.

Appendix A: Acronyms

2HDM	Two-Higgs-Doublet Model
ALICE	A Large Ion Collider Experiment, an LHC detector
AOD	Analysis Object Data (Output of ATLAS Reconstruction)
ASGC	Academia Sinica Grid Computing
ATLAS	A Toroidal LHC ApparatuS, an LHC detector
BNL	Brookhaven National Laboratory
BSM	Beyond the Standard Model
CDF	Collider Detector at Fermilab
CERN	Conseil Européen pour la Recherche Nucléaire
CMS	Compact Muon Solenoid, an LHC detector
CP	Charge and Parity transformation
CS	Central solenoid, part of the ATLAS magnet system
CSC	Cathode Strip Chamber, part of the ATLAS Muon Spectrometer
eV	electron Volt
DAQ	Data Acquisition
dAOD	derived AOD (analysis data format)
dESD	derived ESD (analysis data format)
DPD	Derived Physics Data (analysis data format)
EC	End Cap
ECAL	Electromagnetic Calorimeter
EF	Event Filter (Third ATLAS trigger level)
eFlow	energy Flow (to correct calorimeter energy with tracking data)
ECAL	Electromagnetic CALorimeter
EMEC	Electromagnetic end-cap
ESD	Event Summary Data (Output of ATLAS Reconstruction)
FCAL	Forward Calorimeter, part of the ATLAS hadronic calorimetry
GEANT4	GEometry ANd Tracking 4 (toolkit simulating particles passing matter)
GridPP	Grid for Particle Physics in the UK
GUT	Grand Unified Theory
HCAL	Hadronic CALorimeter
HEC	Hadronic End-Cap, part of the ATLAS hadronic calorimetry
HEP	High Energy Physics
HepMC	HEP Monte Carlo format (standardized event generator output format)
HERWIG	Hadron Emission Reactions With Interfering Gluons (Event Generator)
HLT	High Level Trigger (LVL2 and EF)
ID	Inner Detector, part of the ATLAS Detector
IN2P3	Institut National de Physique Nucléaire et de Physique des Particules

INFN	Istituto Nazionale di Fisica Nucleare
IP1	Interaction Point 1, LHC collision point located in the ATLAS detector
ITC	Intermediate Tile Calorimeter
KIT	Karlsruhe Institute of Technology
LAr	Liquid Argon (Calorimeter), part of the ATLAS calorimetry
LEP	Large Electron-Positron Collider
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty Experiment, an LHC detector
LINAC	LINear ACcelerator
LO	Leading Order
LSP	Lightest Supersymmetric Particle
LVL1	Level 1 (Trigger)
LVL2	Level 2 (Trigger)
MC	Monte Carlo
MDT	Monitored Drift Tube, part of the ATLAS Muon Spectrometer
MSSM	Minimal Supersymmetric Standard Model
NDGF	Nordic DataGrid Facility
NIKHEF	National Institute for Subatomic Physics (formerly: Nationaal Instituut voor Kernfysica en Hoge Energie-Fysica)
NLO	Next-to-Leading Order
NUHM	Non-Universal Higgs Mass (SUSY Scenario)
PIC	Port d'Informació Científica
PS	Proton Synchrotron
PSB	Proton Synchrotron Booster
QCD	Quantum Chromodynamics
QED	Quantum Electrodynamics
RPC	Resistive Plate Chambers, part of the ATLAS Muon Spectrometer
SARA	Stichting Academisch Rekencentrum Amsterdam
SCT	Semiconductor Tracker, part of the ATLAS ID
SM	Standard Model
SPS	Super Proton Synchrotron
SUGRA	SUperGRAvity
SUSY	SUperSYmmetry
tauRec	tau Reconstruction algorithm, used in ATLAS offline reconstruction
TDAQ	Trigger and Data Acquisition
TeV	Tera electron Volt
TileCal	Tile Calorimeter, part of the ATLAS hadronic calorimetry
TGC	Thin Gap Chamber, part of the ATLAS Muon Spectrometer
TRIUMF	Canada's National Laboratory for Particle and Nuclear Physics (formerly: TRI-University Meson Facility)
TRT	Transition Radiation Tracker, part of the ATLAS ID
vev	Vacuum Expectation Value

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