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Search for charged Higgs bosons at the Large Hadron Collider

In autumn 2008 the Large Hardron Collider (LHC) will start operating at CERN in Geneva, offering excellent and absolutely world unique opportunities to make major advances in High Energy Physics research regarding the outstanding question of the Standard Model Higgs boson and, in particular, the various scenarios for new physics beyond the Standard Model. The High Energy Physics Collider Group and the Theoretical High Energy Physics (THEP) Group at the Department of Physics and Astronomy at Uppsala University are currently preparing to make optimal use of the new research facilities and intend to collaborate on, in particular, the search for charged Higgs bosons.

Physics considerations

The origin of mass for elementary particles is one of the outstanding questions in Physics. In the Standard Model, masses are generated for the fermions and for the W- and Z-bosons through the Higgs mechanism, which also predicts the existence of another particle: the scalar Higgs boson. However, the mass of the Higgs boson is not under control in the Standard Model when quantum fluctuations are taken into account. A direct consequence is that the "natural" mass of the Higgs boson is the same as the cut-off scale of the theory, namely the Planck scale where the strength of gravity becomes of the same order as the other interactions.

In order to keep the Higgs mass small, which is needed to ensure tree-level unitarity in WW-scattering and thus the conservation of probability, some kind of symmetry is needed, which keeps the corrections from quantum fluctuations under control. The most celebrated example of such a symmetry is supersymmetry, which predicts the existence of supersymmetric partners to all known particles in such a way that the quantum corrections to the Higgs mass stabilize. The simplest example of a supersymmetric theory is the Minimal Supersymmetric Standard Model (MSSM), which has been widely used as a guideline for what to expect from such a theory in different experiments. However, the number of different possibilities for a consistent supersymmetric theory is very large (with more than one hundred parameters) and therefore one has to resort to just studying some special scenarios where only a handful of the parameters are independent.

In a supersymmetric theory the Higgs mechanism has to be extended to include two Higgs doublets and as a consequence one gets three neutral Higgs bosons and two charged ones. The masses of these Higgs bosons, and the interactions between them, are quite simple to describe compared to the overall complexity of a supersymmetric theory. In the MSSM there are only two parameters at tree-level, which can be chosen to be the mass of the charged Higgs boson and $\tan\beta$, the ratio of the vacuum expectation values of the two doublets, and in the most general two Higgs Doublet Model (2HDM) there are not more than nine additional parameters even when including CP-violation. This makes it possible to conduct more general studies of the possible physics beyond the Standard Model if one limits oneself to the Higgs sector.

The charged Higgs boson is of special interest since its detection would be a definite sign of physics beyond the Standard Model. The coupling of charged Higgs bosons to fermions is proportional to the fermion mass and $\tan\beta$, effectively $(m_t \cot\beta + m_b \tan\beta)$ for top and bottom quarks, and $m_\tau \tan\beta$ for τ leptons. Thus, one needs to investigate search strategies for finding charged Higgs bosons in the plane spanned by the charged Higgs mass and $\tan\beta$ in different scenarios. Since the coupling of the Higgs boson to fermions is proportional to the mass, a proper identification of top quarks and b-jets as well as τ leptons will be essential.

If the mass of the charged Higgs boson is lighter than about 170 GeV (i.e. the difference between the masses of the top and bottom quarks), one should search for $t \rightarrow bH^+$ decays in order to discover (or exclude) light charged Higgs bosons. For Higgs boson masses below the $t\bar{b}$ and SUSY particles production threshold, charged Higgs bosons mostly decay into $\tau^+\nu_\tau$. As a result, an excess of $t \rightarrow b\tau^+\nu_\tau$ decays with respect to other semi-leptonic decays of the top quark ($t \rightarrow b\mu^+\nu_\mu$ and $t \rightarrow be^+\nu_e$ through $t \rightarrow W^+b$) would be a clean signature for the production of charged Higgs bosons.

The top quark pair production cross section at LHC is sufficiently large to ensure that enough data will be taken for precision measurements of the top quarks. At LHC, there will be about $7 \cdot 10^6$ top quark pairs per year at low luminosity and it will be crucial to efficiently identify them, since top quarks appear in many processes. In the charged Higgs boson analysis, one has to search for top quark pairs and accurately measure the cross section of $pp \rightarrow t\bar{t} \rightarrow (b\tau^+\nu_\tau)(\bar{b}jj)$. For this purpose, the Collider Group will need a dedicated analysis tool, i.e. a top quark reconstruction algorithm. Such a tool will certainly be developed within the ATLAS Collaboration also for other purposes and the scope for collaboration of the Uppsala Groups with other research groups in ATLAS on this task needs to be further investigated.

The Collider Group proposes to focus its efforts in particular on the identification of τ leptons, since it is necessary to select events with a τ lepton in the final state when searching for light charged Higgs bosons in top quark decays. The efficiency of a τ analysis tool will critically depend on the performance of the ATLAS SemiConductor Tracker (SCT) detector, which will be used, together with subdetectors in the calorimetric system, to detect the tracks from the 1-prong or 3-prong τ-decays. The Uppsala Collider Group has over the past 10 years contributed to the development and production of the ATLAS SCT detector and has therefore a detailed knowledge of how this detector operates.

At least at low luminosity, the events should be clean enough to allow identification with the SCT of 3-prong decays of the τ leptons, with two same-sign tracks and one track with an opposite sign in the SCT. For the development of an efficient τ-identification tool it will be necessary to understand in detail the distribution of material in the inner detector and to handle correctly the tracks coming from gamma conversions. In the case of 1-prong decays into a pion or longitudinal vector mesons, it will be important to suppress the transverse vector meson contributions, because they dilute the polarization effects in the τ decay, which can be of particular interest when trying to discriminate between charged Higgs bosons and the associated background. One way to perform this suppression is to require that most of the τ-jet energy is carried by the charged track.

After a few years of LHC data-taking at low luminosity the light charged Higgs should have been found if it exists. If this is not the case one must at that time be ready to search for heavier charged Higgs bosons. In this case, the main production process to consider at LHC is $gb \to tH^-$. Under the assumption that there is no decay of the charged Higgs boson into SUSY particles, the main decay to consider is $H^+ \to t\bar{b}$, which leads to final states with three b-jets, but also the subdominant decay $H^+ \to \tau^+\nu_\tau$ is of interest. However, these processes do not allow observation of charged Higgs bosons in the intermediate region around $\tan\beta \sim \sqrt{m_t/m_b} \sim 7$. Another production channel, which has been simulated using Monte Carlo event generators and analysed by the Uppsala Collider Group, is that in which the charged Higgs boson arises from the process $gg \to t\bar{b}H^-$. However, even though in this case the background is reduced by the identification of an extra b-jet, the limited efficiency of the b identification reduces also the signal and no significant improvement has been obtained in this study so far. Including the $gg \to t\bar{b}H^-$ process in the analysis will however allow a more continuous and realistic description of the charged Higgs boson production, in particular for masses close to the top quark mass.

More recently, some other decay channels have been studied by the Uppsala Collider Group where the charged Higgs boson decays into SUSY particles; $H^\pm \to \chi^0\chi^\pm$, and into SM particles; $H^\pm \to h^0W^\pm$. These studies show that, under the assumption of a particular set of values for the MSSM parameters, it would be possible to discover the charged Higgs boson also if the value of $\tan\beta$ would be around 7. For the charged Higgs boson searches it will be important to acquire a more complete understanding of all possible charged Higgs production mechanisms. In particular, they are overlapping in certain regions and proper calculations are needed to get the correct cross section.

The Uppsala THEP Group has recently developed a new method for the proper combination (matching) of the two main mechanisms for producing the charged Higgs bosons in the MSSM, i.e. the $gb \to tH^-$ and $gg \to t\bar{b}H^-$ processes (the inclusion of the latter into the Pythia event generator was also done by members of the group). This allows, for the first time, not only a consistent description of both the high and the low charged Higgs mass regions where the respective processes dominate, but also of the transition between the two. At the same time, one gets, in the case of heavy charged Higgs bosons, a better description of the transverse momentum distribution of the b-jet produced together with the charged Higgs boson and the top quark by combining the two processes (this b-jet will appear also in the dominant production process when one takes into account parton showering and the fact that there are no b-quarks in the initial protons). The implications of this improved description for the potential of experiments at LHC to observe charged Higgs bosons in different scenarios are currently under study in a joint project with the Collider Group. Of special interest is here the difficult transition region between high and low masses for which there currently is no good search strategy.

Another project of the Uppsala THEP Group is to study an alternative production mechanism for charged Higgs bosons, namely $b\bar{b} \to H^+W^-$. According to preliminary results this process may give an additional handle on the transition region discussed above. In addition, it is sensitive to CP-violation effects as well as possible resonance enhancement effects, which may appear in alternative models to the MSSM. However, in order to make more realistic estimation of the usefulness of this process a full ATLAS detector simulation of the process in collaboration with the Collider Group will be necessary.

Quite generally, the full ATLAS detector simulation code will be required in most of the future work in order to get as realistic analysis results as possible. Full simulation is time consuming and it will thus be necessary to have access to considerable computing resources. The Uppsala Collider Group has for this reason taken the initiative to establish a national computing infrastructure based on grid technologies called SweGrid. This computing infrastructure is distributed over six sites in Sweden, each equipped with 100 computing nodes and 15 TB of disk for storing data. The six different sites are connected to form a single grid system using the ARC middleware developed by the NorduGrid project. These facilities are essential for the Swedish groups to be able to simulate ATLAS data and later to analyse the experimental data coming from the ATLAS detector. One of the six SweGrid sites is located at Uppmax (the Uppsala Multidiciplinary Centre for Advanced Computational Science) where the Uppsala Collider Group is involved in the administration of this cluster as well as in the development of the ARC middleware. In preparation for the data analysis, the ATLAS collaboration has performed so-called "data challenges". In these challenges the response of the detector to the particles created in the collision is simulated using Monte Carlo techniques. The idea is to ramp up the scale and the complexity of these challenges to eventually correspond to the situation at the time of the LHC start-up.

The preparatory phase of the physics analysis of ATLAS data

Members of the Uppsala Collider Group will now start to work at CERN on the installation and tests of detector components in ATLAS, in particular for the Semiconductor Tracker detector modules that have been produced in Uppsala in collaboration with groups in Oslo and Bergen, and for the SCT Detector Control System.

It is foreseen that the first year of operation with ATLAS will be dominated by work with the trigger and the data acquisition system, as well as with the calibration and alignment of the various sub-detectors in ATLAS. For this work a good knowledge of the detector hardware is a prerequisite. The Collider Group plans to contribute to the work on the calibration and alignment of the SCT. The group also has a strong interest in the τ trigger and intends to discuss a possible collaboration with the Stockholm High Energy Physics Group on the LVL1 trigger tests and implementation.

The common work of the Collider and THEP Groups to prepare for the physics analysis of the first data to be collected in 2008 has already started and will be successively ramped up as we get closer to the start-up of LHC. One planned project is to analyse jet-production data at high statistics in order to determine the behaviour at LHC of hadronic interactions at very large momentum transfers (several hundred GeV). This analysis is of prime importance to test and verify the Monte Carlo simulation of QCD processes, which will constitute an important background to different possible signals of massive new particles at LHC. The simulation of this background has till now only been made by extrapolating the hadronic-interactions data collected at lower momentum transfers at the Tevatron Collider in USA. Electroweak processes will also be an important part of the background, often constituting a so-called irreducible background, and will thus have to be studied at high statistics and compared to Monte Carlo simulations, especially the description of additional jet activity. One example of this is the decay of the top quark that will constitute an important background in the search for the heavy charged Higgs boson.

A close collaboration between the Collider Group and the THEP Group will be an important asset when trying to understand the early data from ATLAS. The long-term experience of the THEP Group from work with Monte Carlo event generators such as Pythia constitutes an excellent basis for the important task to rapidly arrive at an accurate description of particle production at LHC on the basis of collected data. The generators are able to simulate the production of new particles, such as charged Higgs bosons, according to the theoretical description given by the relevant model (for example the MSSM), as well as the production of the background particles/processes based on experimentally known interactions. The generated data can then be used to identify signatures that the production of new particles (or interactions) would give rise to in an experiment such as the ATLAS detector and also to study how the new particles can be distinguished from known particles and their interactions using these signatures.

From its participation since 2001 in the start-up and running of the D0 experiment at Fermilab's Tevatron, the Uppsala Collider Group has the experience that the work to develop analysis software tools plays a decisive role in the process to arrive at the first physics results after start-up. The data-analysis tools to be developed first for the study of the light charged Higgs bosons, i.e. tools to identify τ leptons, top quarks and b-jets, will most certainly later be useful also for the study of heavy charged Higgs bosons, since the final states are very similar. Another important analysis tool is that by which the energy scale calibration for the calorimeters can be established by comparing the signals from the electromagentic and hadronic calorimeters as well as the track detectors. In our experience it is only when the analysis tools have been well tested on experimental data that reliable physics analysis results can be obtained. The Collider Group therefore intends to focus on the elaboration of some of these analysis tools, primarily those mentioned here, which are important for, among other analyses, the search for the charged Higgs boson.