PROCEEDINGS OF SCIENCE

Outlook on the prospects for charged Higgs discovery

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A brief overview of the current status of indirect and direct searches for the charged Higgs boson at the B factories and the LHC is given and, on the basis of this, the prospects for a discovery of the charged Higgs boson during the remainder of the current decade is discussed.

Prospects for Charged Higgs Discovery at Colliders
October 8-11, 2012
Uppsala University Sweden

[1] Speaker

1.Introduction

The discovery of the charged Higgs boson may well become one of the first, or even the first, concrete signs of Beyond the Standard Model (BSM) physics. If and when discovered, our first task will be, like for the recently discovered neutral Higgs-like boson, to make precision measurements of the H+ (here H+, or H- in some figures, is used as a shorthand for charged Higgs, the charged conjugate state being implied) mass, total width, spin and couplings in order to get indications of the specific BSM scenario chosen by Nature.

There is a natural sequence of the expected future contributions to the search for H+ from experiments at current and future accelerators. B Super Factory experiments are already providing indirect information on the H+ from rare B decays leading to model dependent bounds on the H+ mass and, possibly, in the future to indirect indications of the existence of the H+. The LHC experiments ATLAS and CMS have so far provided bounds from direct H+ searches which typically are lower than those from the B factories, but they have the potential to discover the H+ through direct observation of, first, a light H+ (i.e. a H+ of mass below that of the top quark) and later, after the LHC upgrade, of a heavy H+. Already, we may conclude that the LHC has significantly reduced the likelihood for the discovery of a light H+. Eventually, future e^+e^- colliders will provide the opportunity to make high precision measurements of a H+ already discovered at the LHC. Alternatively, if at that time the LHC has not discovered a H+ and if the energy of the future e^+e^- collider is high enough, like at e.g. CLIC, a H+ in a region of parameter space inaccessible at LHC could be discovered in e^+e^- collisions.

2. Indirect detection at B factories

The role played in the Standard Model (SM) by the W+ (the charge conjugate W- state is implied throughout this paper) in weak decays provides a plethora of opportunities to search for effects of the H+, as the H+, if it exists, in principle can be thought to contribute, as an alternate to the W+, in all weak decays and in particular the decay of the heavy b quark. So, if a significant discrepancy was found between the SM rate and the experimentally observed rates of rare B decays, this could be taken as an indication of the existence of the H+ although other explanations may also be hypothesized. Such discrepancies are currently observed in various rare B decays but, so far, none with sufficient significance to be fully convincing.

2.1 The decay b→sγ

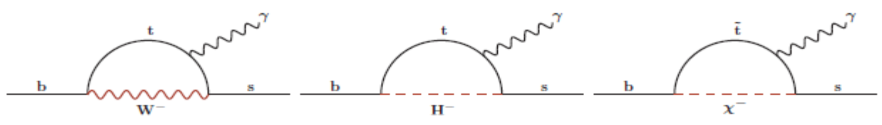


Figure 1: The decay b→sγ with tree different intermediate bosons.

Flavor changing neutral currents like in B decays to a K together with other light mesons and a gamma, may occur at first order through radiative loop diagrams. Figure 1 shows three first order diagrams for how a b quark can change into an s quark through an intermediate t quark radiating a gamma. The intermediate boson can be a W+, a H+ or a chargino χ+. The charged Higgs boson will always add constructively to the first SM diagram whereas a chargino can interfere constructively or destructively. Measurements of many different decays of the type B decaying to K together with other light mesons and a gamma, at Belle and Babar have yielded a value for the branching fraction BR(B→Xs) = $(3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$ [1] which is not significantly different from the latest calculated NNLO SM result $(3.15 \pm 0.23) \times 10^{-4}$ [2,3]. NNLO calculations have also been made in Two Higgs Doublet Models (THDM) type-II leading to a lower bound on the H+ mass of 380 GeV at 95% confidence level (CL) [4]. Also SUSY NNLO calculations have been made which give weaker limits on the H+ mass.

2.2 The decay B→τν

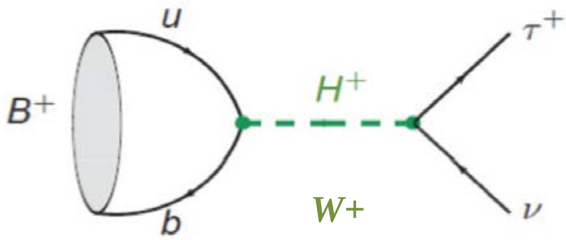


Figure 2: The decay B→τν with a H+ or W+ as intermediate boson.

Figure 2 shows the SM first order diagram for the decay of a B meson to τν and how the same decay can proceed with a H+ as intermediate boson. The latest value for the branching ratio for this decay reported by Belle at the ICHEP 2012 conference is BR(B→ τν) = 0.72±0.25±0.11 [5]. This brings the world measured average of this BR, which before the Belle report was 3 σ above the SM theoretical value of 0.75±0.15, down to BR(B→ τν) = 1.14±0.23, which is compatible, within uncertainties, with the SM value and does not leave much room for a low mass H+.

2.3 The ratio B→D(*)τν/B→D(*)lν

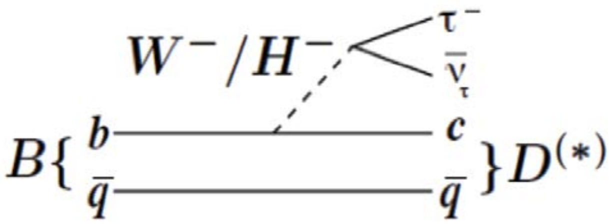


Figure 3: The decays B→D and B→D* proceeding through W+ or H+ emission and subsequent decay to $\tau\nu_\tau$.

The transition of the b quark to a c quark in B to D decays proceeds in the SM through emission of a W+ that decays to the three lepton flavors whereas, if the decay would proceed through H+ emission, the decay lepton flavor would predominantly be that of the tau. The presence of a H+ will thus increase the ratio R of the rate of $B \to D^{(*)}\tau\nu$ to that of $B \to D^{(*)}l\nu$, where l=e, μ or τ, with respect to its SM value. Recent high precision SM calculations have resulted in values for R of 0.297±0.007 and 0.252± 0.003 for B→D and $B \to D^{*}$, respectively [6]. The latest BaBar measurement of the same ratios R have yielded the values 0.440±0.071 and 0.332±0.029, respectively [7], which together are in 3.4σ disagreement with the calculated SM R values, providing room for a possible H+ contribution. Interpreting this contribution in the type II THDM model yields values of the ratios as function of the parameter $\tan\beta/m_{H+}$, where tanβ is the ratio of vacuum expectation values of the two Higgs doublets and m_{H+} is the charged Higgs mass. The two measured ratios would correspond to $\tan\beta/m_{H+}$ values of 0.44±0.02 and 0.75±0.04 for D and D*, respectively (see Fig. 4 from [7]), which excludes the type II THDM model as an explanation of the R measurements at 99.8% CL. Future measurements, like those planned at Belle, may reduce this discrepancy or one would have to look for other models than the type II THDM.

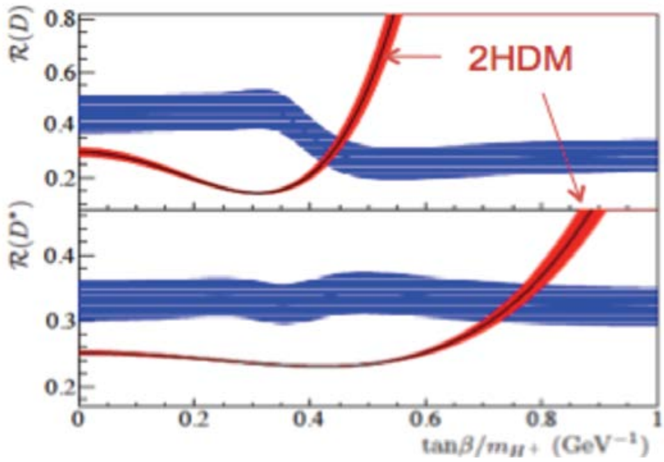


Figure 4: The ratio $B \to D^{(*)}\tau\nu / B \to D^{(*)}l\nu$ versus $\tan\beta/m_{H+}$ as measured by BaBar (blue horizontal bands) and as calculated in the type II THDM model (red bands marked 2HDM) [7].

3. Indirect and direct detection at the LHC

In addition to the complementary indirect measurements of H+ that can be made in B decays at the LHC, there is the possibility of discovery of the H+ through the observation of direct production and decay of on-shell H+.

3.1 The decay $B_s^0 \to \mu^+\mu^-$

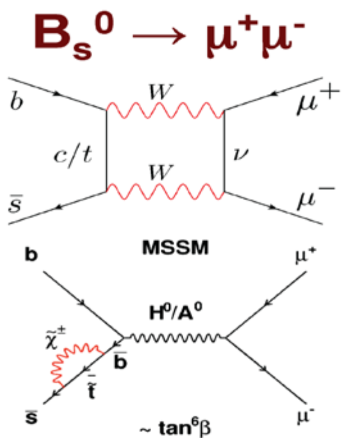


Figure 5: The second order $B_s^0 \to \mu^+\mu^-$ weak decay can in the SM proceed through the emission of two intermediate W+, one or both of which could be a H+ in a non-SM scenario. In MSSM the intermediate state can be a H^0 or a A^0 with a chargino radiative correction in the initial state.

In the SM $B_s^0 \to \mu^+\mu^-$ is a second order weak decay which has recently been calculated to have a BR of $(3.2\pm0.2)*10^{-9}$ [8]. Searches by LHCb, ATLAS and ALICE have so far yielded an upper limit on this BR of $4.2 *10^{-9}$ [9] close to the SM value. Any deviations from the SM could be explained in e.g. THDM scenarios in which the W+ is replaced by a H+ or in Minimal Super Symmetric Model (MSSM) scenarios in which other SUSY particles contribute as intermediate states. When the full luminosity of the 2012 LHC run will be analyzed with improved techniques the SM level will presumably be reached, constraining any contribution with constructive interference with the SM to be very small or possibly providing an indication of a contribution with significant destructive interference. (Note added in proof; In January 2013 LHCb published [10] the observation of a $B_s^0 \to \mu^+\mu^-$ signal with a CL of 3.5 σ and a BR of $(3.2^{+1.5}_{-1.2})*10^{-9}$.)

3.2 Combined exclusion from rare decays mediated by H+

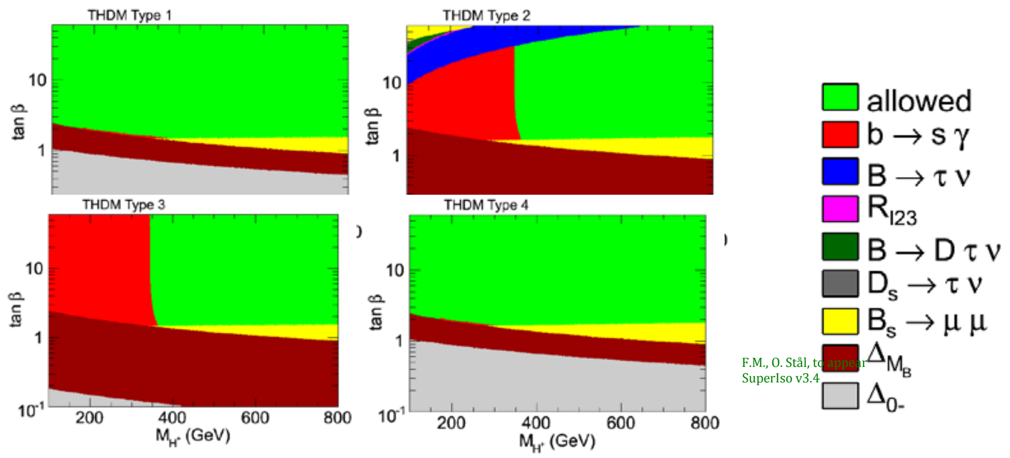


Figure 6: Limitations imposed by the various rare decays measurements in the tanβ vs m_{H+} planes of four types of the THDM model.

Figure 6 shows the limitations imposed by all four rare B decay measurements discussed above ($b \to s\gamma$, $B \to \tau\nu$, $B \to D\tau\nu$ and $B_s^0 \to \mu^+\mu^-$) in the tanβ vs m_{H+} planes of the four types of the THDM model. The bound $m_{H+}<380$ GeV from $b \to s\gamma$ in the type-II model is clearly seen and it also appears for the type-III model whereas, for the type-I and type-IV models, there is no lower H+ mass bound above 100 GeV for tanβ values above 3.
In 2014 the SuperKEKB will start operation and it is foreseen that by 2018 50 ab^{-1} will have been accumulated, about 50 times the integrated luminosity of KEKB. With this the indirect searches for H+ will be substantially extended with the prospects of detecting effects of, or excluding, very heavy H+.

3.3 Direct detection at the LHC

At the LHC a H+ lighter than the top quark can be detected in the decay of the top quark and a H+ heavier than the top quark can be detected through its decay to a tb quark pair or to a τ and a ν_τ.

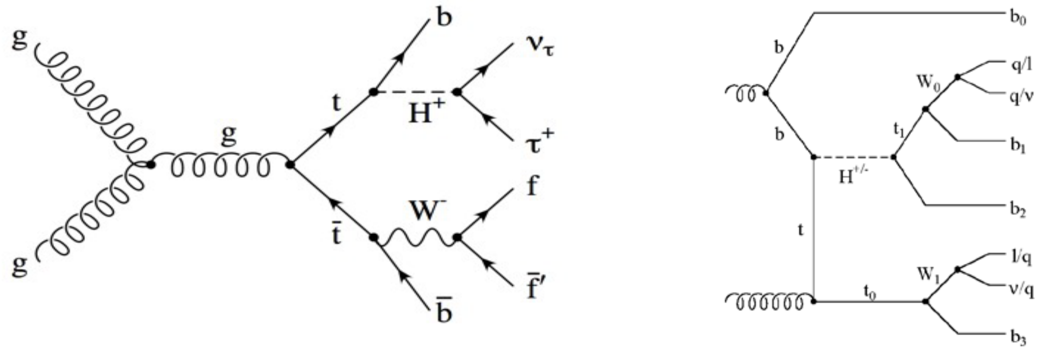
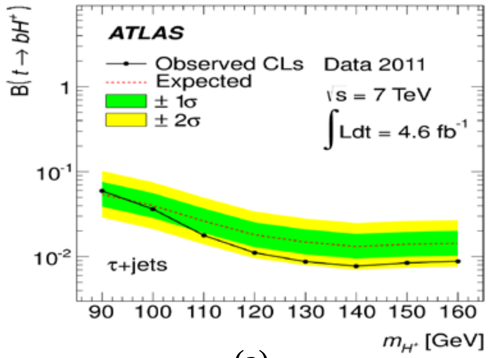


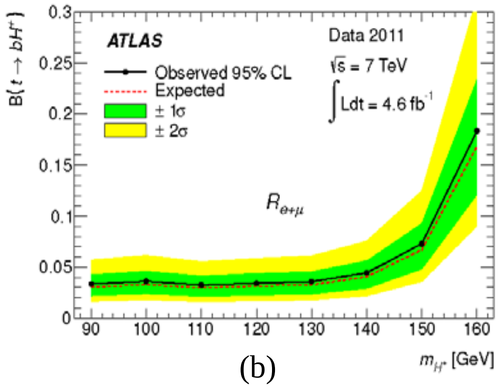
Figure 7: To the left the production and decay of the light H+ ($m_{H+}<m_{top}$) to a τ and a ν_τ and to the right of the heavy H+ ($m_{H+}>m_{top}$) to a tb quark pair.

So far only searches for light H+ have produced significant results at the LHC. The basic search method for the light H+ is to look for the two predominant decay channels for the H+, $\tau\nu_\tau$ for high tanβ values and $c\bar{s}$ for low tanβ values. An alternative method for high tanβ values, called the ratio method, is to look for deviations from lepton universality in $t\bar{t}$ decays, interpreting any significant deviation as a result of that some fraction of the t quarks decay to bH+ and the H+ decays only to $\tau\nu_\tau$, i.e. not like the W+ also to $e\nu_e$ and $\mu\nu_\mu$. ATLAS has performed both types of analysis for high tanβ, in both cases assuming BR(H+→ $\tau\nu_\tau$) = 1, that are based on 4.6 $fb^{-1}$of data, obtaining upper limits on the t→H+b branching ratio in the mass range 90-160 GeV. The analysis based on the reconstruction of the H+→$\tau\nu_\tau$ decay in $t\bar{t}$ events [11] attains the lowest upper limits on the t→H+b branching ratio at high H+ masses (Figure 8a) and the analysis based on the ratio method [12] attains the lowest upper limits at low H+ masses (Figure 8b). Combining the two results provides an upper limit on the t→H+b branching ratio which varies between 0.8% and 3.4% within the mass H+ mass range (Figure 8c). Assuming the m_h-max MSSM scenario, upper limits on the t→H+b branching ratio can be translated into the exclusion limits in the tanβ vs m_{H+} plane shown in Figure 8d [12]. Assuming in addition that that the recently observed Higgs-like boson is the lighter CP-even Higgs (h^0) and taking into account the experimental exclusion of a second neutral

Higgs (H or A), results in the additional red and white exclusion area in Figure 8e for $X_t = -2\text{TeV}$ [13].



(a)



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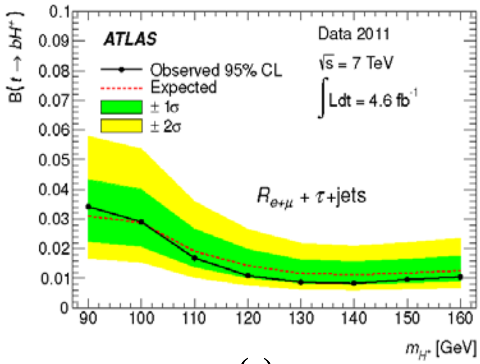

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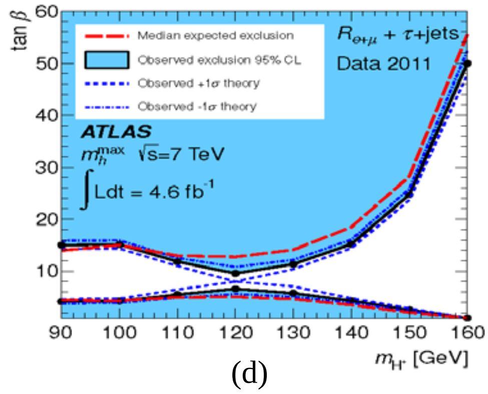

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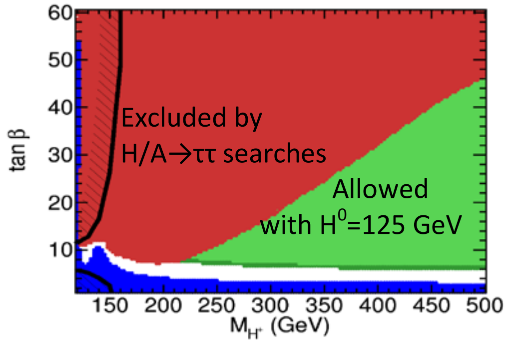

(e)

Figure 8: Upper limits on BR(t→H+) obtained in ATLAS from the reconstruction of the H+→ $\tau\nu_\tau$ decay in $t\bar{t}$ events (a) [11] and from the ratio method, based on the lepton universality in $t\bar{t}$ events (b) [12] as well as the combined upper limit from these two complementary analyses (c) [12]. Interpreting this upper limit in the m_h-max scenario results in the blue exclusion areas in the MSSM tanβ vs m_{H+} plane in (d) [12]. Assuming in addition that the recently observed Higgs-like boson is the lighter CP-even Higgs (h^0) and taking into account the experimental exclusion of a second neutral Higgs (H or A) and setting $X_t = -2\text{TeV}$ results in the red and white exclusion areas in (e) (the blue area is excluded by LEP) [13].

In these analyses with 4.6 fb^{-1} of LHC data the statistical errors are still significant and it will be interesting to see what the same analyses of the full 2012 LHC data sample will give. Since the values of the t→H+b branching fraction are at most on the percent level, this does not leave much room for m_{H+} below the top mass in the tanβ vs m_{H+} MSSM parameter space. Furthermore, the indications from the indirect studies measuring rare B decays are also that the likelihood for a low mass H+ has become very limited.

Direct searches for H+ heavier than the top mass in the decay H+→tb have already started in ATLAS and CMS. However, pushing to higher masses will require a lot of luminosity. With the LHC data accumulated during 2012 some progress could be made but to obtain a substantial reach towards higher H+ masses we will have to wait for the full luminosity, full energy LHC runs after the 2013-2014 long shut-down.

So far we have been looking for the light H+ decaying to $\tau\nu_\tau$ or $c\bar{s}$ and the heavy H+ decaying to $\tau\nu_\tau$ or tb. There are other possible non-SM decay channels like $H+\rightarrow\chi^+\chi^0$ and $H+\rightarrow Wh^0$ and, in the so called Flipped Model of type III, the light H+ decays predominantly to bc. In other more exotic models, presented at this workshop [14], H+ decays to cs, cb, ts, Wγ and WZ, so we need to keep an open mind as to what H+ decay states to look for….

4. Linear colliders

Given the now limited likelihood for a light H+ it is not likely that a 250 GeV e^+e^- collider Higgs factory or 350 GeV e^+e^- collider $t\bar{t}$ factory would be useful for H+ studies. However, a several TeV e^+e^- collider like CLIC could provide not only precision studies of a heavy H+ discovered at LHC but also discovery potential for heavy H+ beyond the LHC H+ reach. A recently published study [15] concluded that the statistical error in the mass determination of a 900 GeV mass H+ could be made as small as 2.4 GeV and that of the width determination 5.4 GeV, see Figure 9.

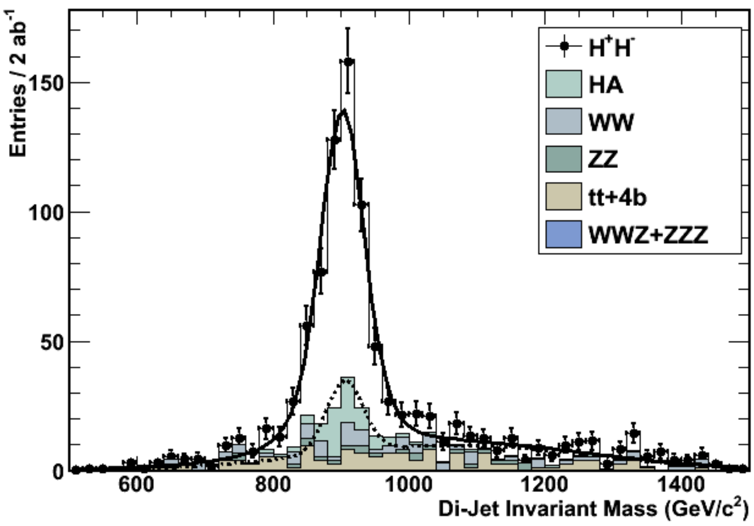

Figure 9: Simulated H+ signal and SM background at CLIC. A fit to the data results in m_{H+}= (902.6±2.4 (stat)) GeV and Γ_{H+} = (20.2±5.4(stat)) GeV [15].

5. Outlook

During the LHC shut-down years 2013 and 2014 the LHC data collected until the end of 2012 will be reanalyzed with high accuracy. With BR(t→H+b) less than a few percent and no second neutral Higgs boson found below order 450 GeV mass, there is limited chance that a H+ lighter than the top quark would be found. The direct search in LHC data for H+ with a mass above that of the top quark is starting now and, as this search enters virgin territory, there is still some chance that a discovery will be made in the 2012 data. When the LHC will start up again at the end of 2014 SuperKEKB will just have started up. By 2016 LHC is foreseen to have collected some 50-100 fb^{-1} at 13 TeV collision energy and SuperKEKB some 10 ab^{-1}, which is 10 times more than KEKB. By 2018 LHC may have reached 100-200 fb^{-1} and SuperKEKB some 25 ab^{-1} and by 2020 LHC may have accumulated as much as 200-400 fb^{-1} and SuperB 50 ab^{-1}. So there are indeed good prospects for finding new high mass states, and among those the H+, during the remainder of the current decade.

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