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Future charged Higgs boson search prospects at LHC

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The charged Higgs boson searches published so far by the ATLAS and CMS experiments at the CERN LHC are reviewed. The development of the sensitivity of the measurements is presented. An estimate is given for what could be achieved with the data collected during 2012 and possible bottlenecks for improving the sensitivity of the measurements are discussed.

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1. Introduction

The searches for charged Higgs bosons at LHC have undergone rapid changes and developments in the past few years. Up to 2008, the ATLAS [1] and CMS [2] experiments had done simulation-based feasibility studies and plans for background measurements. In 2010, first data arrived and allowed for first measurements of basic physics objects and of some of the backgrounds essential for the charged Higgs boson searches. Two years later, both the ATLAS and CMS experiments were able to independently set a stringent upper limit on the branching $\mathscr{B}(\mathrm{t} \to \mathrm{bH}^+)$ for $m_{\mathrm{H}^+} < m_\mathrm{t} - m_\mathrm{b}$ based on measurements on the $\mathrm{H}^+ \to \tau\nu_\tau$ decay channel in $\mathrm{t\bar{t}}$ production [3, 4], thus improving the limit set by Tevatron experiments [5, 6] by up to a factor of ten.

In this paper, an estimate is given for what could be the coverage of the ATLAS and CMS searches in 2014. Such a future scenario is well defined, since the LHC will enter its first long shutdown period during 2013-2014 to increase the collision energy. Therefore, the data available for the searches is the data collected during the years 2011-2012, i.e. 5 fb^{-1} at $\sqrt{s} = 7$ TeV and $\sim$20 fb^{-1} at $\sqrt{s} = 8$ TeV. For simplicity, a two Higgs doublet model is assumed in the presented estimates with the MSSM $m_\mathrm{h}^\mathrm{max}$ scenario [7] chosen as a benchmark. The charged Higgs boson production cross sections are obtained from Refs. [8, 9] and the FeynHiggs [10] program is used to evaluate the branching ratios of the charged Higgs bosons.

2. Current searches for light charged Higgs bosons and their prospects

The light charged Higgs bosons are produced via $\mathrm{t\bar{t}}$ and single top production with at least one top quark decaying through $\mathrm{t} \to \mathrm{bH}^+$. For $\tan\beta > 5$, the charged Higgs bosons prefer to decay to $\tau\nu_\tau$, with $\mathscr{B}(\mathrm{H}^+ \to \tau\nu_\tau) > 95\%$ in the $m_\mathrm{h}^\mathrm{max}$ scenario. The subleading decay modes are $\mathrm{H}^+ \to \mathrm{c\bar{s}}$ which is important for probing low $\tan\beta$ and, although being suppressed by a CKM matrix element, $\mathrm{H}^+ \to \mathrm{c\bar{b}}$.

Both ATLAS and CMS collaborations have published results on the $\mathrm{H}^+ \to \tau\nu_\tau$ decay channel. In the publication with 4.6 fb^{-1} of 2011 data, ATLAS combined the results of the fully hadronic ($\mathrm{t\bar{t}} \to (\mathrm{bH}^+)(\mathrm{\bar{b}W}^-) \to (\mathrm{b}\tau_\mathrm{h}\nu_\tau\bar{\nu}_\tau)(\mathrm{\bar{b}q\bar{q}}'))$, the tau+lepton ($\mathrm{t\bar{t}} \to (\mathrm{b}\tau_\mathrm{h}\nu_\tau\bar{\nu}_\tau)(\mathrm{\bar{b}}\ell\nu_\ell)$), and the lepton+jets ($\mathrm{t\bar{t}} \to (\mathrm{b}\tau_\ell\nu_\tau\bar{\nu}_\tau\nu_\ell)(\mathrm{\bar{b}q\bar{q}}')$) final states, where τ_h denotes a hadronic τ decay, τ_ℓ denotes a leptonic τ decay, and $\ell = \mathrm{e}, \mu$ [3]. The CMS paper with 2.3 fb^{-1} of 2011 data considered the fully hadronic, the tau+lepton, and the di-lepton ($\mathrm{t\bar{t}} \to (\mathrm{b}\tau_\ell\bar{\nu}_\tau\bar{\nu}_\ell)(\mathrm{\bar{b}}\ell\bar{\nu}_\ell)$) final states [4]. In both experiments, the fully hadronic final state was found to be the most sensitive final state because it allows for the reconstruction of the charged Higgs boson transverse mass with all missing energy in the event coming from the charged Higgs boson decay.

The ATLAS collaboration has measured also an upper limit on $\mathscr{B}(\mathrm{t} \to \mathrm{bH}^+)$ with the $\mathrm{H}^+ \to \mathrm{c\bar{s}}$ final state using 4.7 fb^{-1} of 2011 data [11].

Compared to the data collected in 2011, in the 2012 data the number of expected signal events increases by a factor of $\sim$6.5 because of the $\sim$40% increase in the $\mathrm{t\bar{t}}$ cross section. From the conducted searches it is clear that the $\mathrm{H}^+ \to \tau\nu$ decay mode is the most sensitive one for finding or exluding the light charged Higgs bosons. Assuming $\mathscr{B}(\mathrm{H}^+ \to \tau_{\nu_\tau}) = 1$ and a selection efficiency of 0.01, the number of expected signal events in the fully hadronic final state becomes ~ 1100 with 2011+2012 data. The increase in data can be expected to set a new lower bound for the mass of the light charged Higgs bosons. To exclude charged Higgs bosons of mass 160 GeV/c^2 in the $m_{\mathrm{h}}^{\mathrm{max}}$ scenario, one would need to set a limit $\mathscr{B}(\mathrm{t} \to \mathrm{bH}^+) \lesssim 0.001$, which is about ten times better than the current limit. It seems therefore evident, that adding the 2012 data to existing analyses is not enough to reach the required sensitivity to exclude charged Higgs bosons in the $m_{\mathrm{h}}^{\mathrm{max}}$ scenario with masses below 160 GeV/c^2 at 95% CL. On the other hand, should a signal be present in the data, first indications of it should become visible with the 2011+2012 data.

3. Current searches for heavy charged Higgs bosons and their prospects

The production of the heavy charged Higgs bosons proceeds through the $\mathrm{gg} \to \bar{\mathrm{t}}\mathrm{bH}^+$ and $\mathrm{gb} \to \bar{\mathrm{t}}\mathrm{H}^+$ processes. The former is the so-called five-flavour scheme and the latter the so-called four-flavour scheme. They yield the same production cross section at sufficiently high-order calculation. It should be noted that for the $\mathrm{H}^+ \to \tau\nu_\tau$ decay mode the final state is the same for the heavy charged Higgs bosons as for the light charged Higgs bosons produced in $\mathrm{t\bar{t}}$ decay.

The branching fraction of $\mathrm{H}^+ \to \tau\nu_\tau$ decreases rapidly as a function of m_{H^+}, but increases as a function of $\tan\beta$. The branching ratio of $\mathrm{H}^+ \to \tau\nu_\tau$ is sizeable in the $m_{\mathrm{h}}^{\mathrm{max}}$ scenario in most parts of the range $m_{\mathrm{H}^+} = 200-500$ GeV/c^2 and $\tan\beta = 10-50$. The decay mode $\mathrm{H}^+ \to \mathrm{t\bar{b}}$ starts to dominate for $m_{\mathrm{H}^+} \gtrsim 220$ GeV/c^2 and is suppressed by the $\mathrm{H}^+ \to \chi^+\chi^0$ processes once the neutralinos and charginos become kinematically available.

Because of the predicted small production cross section of the heavy charged Higgs bosons and the large cross section of the backgrounds, only simulation-based feasibility studies have so far been conducted by the ATLAS and CMS collaborations. In the $\mathrm{H}^+ \to \tau\nu_\tau$ decay mode with a fully hadronic final state, the signal has been shown to be separable from the electroweak and $\mathrm{t\bar{t}}$ backgrounds by reconstructing the transverse mass of the charged Higgs boson [12, 13]. Therefore, it is considered to be the most promising channel to look for heavy charged Higgs bosons. In the $\mathrm{H}^+ \to \mathrm{t\bar{b}}$ decay mode with its $\mathrm{bb\bar{b}\bar{b}q\bar{q}}'\ell\nu_\ell$ final state, where $\ell = \mathrm{e}, \mu$, the reconstruction of the charged Higgs boson invariant mass is possible and the branching fraction is larger than in the $\mathrm{H}^+ \to \tau\nu_\tau$ decay mode in most parts of the parameter space [14, 13]. Solving the combinatorics and suppressing the large $\mathrm{t\bar{t}}$ background make the analysis, however, challenging. The most promising final state to look for $\mathrm{H}^+ \to \chi^+\chi^0$ is $\ell\ell\ell\nu_\ell\tilde{\chi}^0\tilde{\chi}^0$ according to feasibility studies [15, 16]. The analysis of this final state relies heavily on the assumption of the mass spectrum of the supersymmetric particles and on identifying the signal against a large background of supersymmetric particles. A more exotic decay mode $\mathrm{H}^+ \to \mathrm{Wh}^0$ has also been studied [17], but its branching ratio is more than ten times smaller than that of the $\mathrm{H}^+ \to \tau\nu_\tau$ decay mode.

In the $m_{\mathrm{h}}^{\mathrm{max}}$ scenario, the expected number of signal events for $m_{\mathrm{H}^+} = 200$ GeV/c^2 at $\tan\beta = 50$ for the 2011+2012 data is of the order of 13000. Therefore, since the branching ratio multiplied by the selection efficiency needs to be $\sim 10^{-4}$ to obtain just one signal event on top of a non-negligible background, minor decay modes, such as $\mathrm{H}^+ \to \mathrm{Wh}^0$, have too low yield to be searched for, at least for the $m_{\mathrm{h}}^{\mathrm{max}}$ scenario. For the most promising decay modes, the number of expected signal events with 2011+2012 LHC data is shown in Table 1 in the range $m_{\mathrm{H}^+} = 200$ to 500 GeV/c^2 and $\tan\beta = 10$ to 50. The selection efficiencies have been assumed to conform with the published feasibility studies. Since in the $\mathrm{H}^+ \to \tau\nu_\tau$ decay mode the signal and background are separable through the reconstruction of the transverse mass of the charged Higgs boson and since in the other

	Decay mode	$\varepsilon_{\text{selections}}$	$m_{\mathrm{H}^+} =$ 200 GeV/c^2	$m_{\mathrm{H}^+} =$ 300 GeV/c^2	$m_{\mathrm{H}^+} =$ 400 GeV/c^2	$m_{\mathrm{H}^+} =$ 500 GeV/c^2
$\tan\beta = 50$	$\mathrm{H}^+ \to \tau\nu_\tau$	0.01	84	13	3.8	1.4
	$\mathrm{H}^+ \to \mathrm{t\bar{b}}$	0.01	30	33	13	5.7
	$\mathrm{H}^+ \to \chi^+\chi^0$	0.1	<0.01	15	19	15
$\tan\beta = 30$	$\mathrm{H}^+ \to \tau\nu_\tau$	0.01	29	4.2	1.1	0.4
	$\mathrm{H}^+ \to \mathrm{t\bar{b}}$	0.01	12	12	4.5	1.6
	$\mathrm{H}^+ \to \chi^+\chi^0$	0.1	<0.01	13	9.2	11
$\tan\beta = 10$	$\mathrm{H}^+ \to \tau\nu_\tau$	0.01	2.9	0.2	0.05	0.01
	$\mathrm{H}^+ \to \mathrm{t\bar{b}}$	0.01	1.6	1.0	0.3	0.07
	$\mathrm{H}^+ \to \chi^+\chi^0$	0.1	<0.01	7.1	3.8	2.7

Table 1: Number of expected signal events for the 2011+2012 LHC data in the $m_{\mathrm{h}}^{\max}$ scenario for the most promising decay channels for m_{H^+} range 200 to 500 GeV/c^2 and $\tan\beta$ range 10 to 50. At $m_{\mathrm{H}^+} = 200$ GeV/c^2 the neutralino or chargino would be virtual because of the choice of their masses in the $m_{\mathrm{h}}^{\max}$ scenario.

decay modes the separaration of signal and background is challenging, it can be concluded based on Table 1 that the $\mathrm{H}^+ \to \tau\nu_\tau$ decay mode is the most promising decay mode for finding a first hint of the charged Higgs bosons or to set exclusion limits. Based on the estimated number of signal events, it is reasonable to expect that some region of the $m_{\mathrm{H}^+}, \tan\beta$ parameter space can be experimentally probed with the 2011+2012 LHC data.

4. Development of the sensitivity of the existing analyses

To assess the reach of future H^+ studies, the development of the sensitivity of the analyses done so far needs to be understood. The measure of sensitivity of the analyses of the $\mathrm{H}^+ \to \tau\nu_\tau$ decay mode is given by the model independent expected upper limit on $\mathscr{B}(\mathrm{t} \to \mathrm{bH}^+)$ at 95% confidence level (CL).

The CMS collaboration has published two preliminary results and a final result on the 95% CL upper limit on $\mathscr{B}(\mathrm{t} \to \mathrm{bH}^+)$ with 36 pb^{-1} of 2010 data, 1.0 fb^{-1} of 2011 data, and 2.3 fb^{-1} of 2011 data, respectively. With 36 pb^{-1} of 2010 data and considering the lepton+jets final states, the expected 95% CL upper limit was found to be between 24% at $m_{\mathrm{H}^+} = 80$ GeV/c^2 and 56% at $m_{\mathrm{H}^+} = 160$ GeV/c^2 [18]. In the 1.0 fb^{-1} analysis, the expected 95% CL upper limit decreased to 12% for $m_{\mathrm{H}^+} = 80$ GeV/c^2 and to 3% for $m_{\mathrm{H}^+} = 160$ GeV/c^2 [19]. The improvement was based on the increased luminosity and on the addition of the fully hadronic final state to the limit calculation. In the paper with 2.3 fb^{-1} of 2011 data, the expected 95% CL upper limit further decreased to 2.9% for $m_{\mathrm{H}^+} = 80$ GeV/c^2 and to 1.1% for $m_{\mathrm{H}^+} = 160$ GeV/c^2 [4]. The improvement with respect to Ref. [19] was driven by converting the analysis of the fully hadronic final state from a counting experiment to a shape analysis. Also some key systematical uncertainties relying on statistical properties of certain measurements decreased and the di-lepton channel was added to the combined limit.

The ATLAS collaboration has published a preliminary result and a final result on the 95% CL upper limit on $\mathscr{B}(\mathrm{t} \to \mathrm{bH}^+)$ with 1.0 fb^{-1}, and 4.6 fb^{-1} of 2011 data, respectively. In the 1.0 fb^{-1}

analysis, the best expected 95% CL upper limit of 6.0% for $m_{\mathrm{H}^+} = 90$ GeV/c^2 and of 2.0% for $m_{\mathrm{H}^+} = 160$ GeV/c^2 was obtained with the fully hadronic final state [20]. The limit was obtained based on a shape analysis. In the 4.6 fb^{-1} paper, the expected 95% CL upper limit decreased to 3.4% for $m_{\mathrm{H}^+} = 90$ GeV/c^2 and to 1.1% for $m_{\mathrm{H}^+} = 160$ GeV/c^2 [3]. Compared to the limit in Ref. [20], the tau+lepton and lepton+jets final states, based on a shape analysis, were added. The fully hadronic analysis remained essentially the same as before and the improvement of the expected 95% CL upper limit was driven by the increase of luminosity.

5. Improving the sensitivity of the existing analyses

In the following subsections, a few general possibilities to improve the sensitivity of the existing H^+ searches are outlined.

5.1 Improving sensitivity by increasing luminosity

The first obvious possibility to improve sensitivity of the results is to increase the luminosity of the measurement. When the uncertainty of a measurement is dominated by statistical uncertainty, the sensitivity will improve by the square root of the luminosity of the new measurement divided by the square root of the luminosity used in the old result, assuming that the measurement methods and conditions remain unchanged. This condition is valid for the searches of the heavy charged Higgs bosons. The $\mathrm{H}^+ \to \tau\nu_\tau$ analyses for the light charged Higgs are, however, already dominated by systematical uncertainties. In that case, adding luminosity will not improve sensitivity of the analysis. An example of such "systematics barrier" can be seen in the simulated estimate of the 95% CL upper limit on $\mathscr{B}(\mathrm{t} \to \mathrm{bH}^+)$ in the fully hadronic final state of the $\mathrm{H}^+ \to \tau\nu_\tau$ search in Ref. [12]. A commonly used technique to fight the "systematics barrier" is to split the measurement into smaller orthogonal pieces of phase space that are combined by statistical methods. For example, the sensitivity of the CMS fully hadronic final state analysis of the $\mathrm{H}^+ \to \tau\nu_\tau$ search was considerably improved by transforming the counting experiment in Ref. [19] into a shape analysis in Ref. [4]. An analysis that already applies shape analysis could be transformed to use multi-dimensional shapes. Another possibility to divide the measurement phase-space is to use orthogonal selection categories. Applying such measures come, however, with a cost of requiring a lot of optimisation thus increasing the need for manpower and computing resources. Furthermore, they tend to cause the loss of overview of the physical principles why the analysis works.

In practice, adding luminosity to the analysis always means changing conditions. For example, an increase in the instantaneous luminosity of the collider and therefore in the number of interactions per bunch crossing may necessitate increased $\mathrm{E_T}$ thresholds at trigger level. The increased number of pile-up events complicates the analysis, because one needs to add further event selections, apply correction factors, and possibly increase the offline thresholds for reconstructed physics objects. Furthermore, the detectors measuring the particle collisions are subjected to high doses of radiation. These effects all lead to loss of acceptance or increase of systematical uncertainties thus worsening the sensitivity of the analysis. On the other hand, many of the systematical uncertainties, such as for example the trigger efficiency measurement uncertainty, are typically estimated by a counting experiments and are therefore statistical by nature. Consequently, such uncertainties will become smaller when luminosity is added to the analysis and the sensitivity of the analysis will be improved.

5.2 Improving sensitivity by better physics objects performance

The charged Higgs boson searches depend on the performance of almost all reconstructed physics objects. In the fully hadronic final state, the reconstruction of the jets, b jets, missing transverse energy, and hadronic tau decays yield the largest impact on the analysis sensitivity. Major improvements in the reconstruction of these objects have taken place since the feasibility analyses, most notably because of the particle flow algorithm of CMS [21]. Further improvements could be expected to take place with improved understanding of the detector calibrations. The largest improvement to the analysis sensitivity should, however, come at this stage from making the reconstruction of the physics objects as robust as possible against the high number of pile-up events.

5.3 Improving sensitivity by better signal separation

To separate better the signal and background events one needs to understand better the data-driven background measurements. For example, in the fully hadronic $\mathrm{H}^+ \to \tau\nu_\tau$ analyses, the QCD multi-jet background favors collinear and back-to-back configurations of the jet misidentified as the hadronic tau and of the misidentified missing transverse momentum. As demonstrated in Ref. [4], by suppressing the back-to-back component, which has a high probability to end up in the signal region in the transverse mass spectrum, the sensitivity for signal is increased.

Another option to improve signal separation from backgrounds, that has not yet been applied in current analyses, is to use multivariate methods to select the signal enriched phase space more efficiently. The gain from multivariate methods is usually up to few tens of percents in sensitivity, but the price is that the analysis becomes more laborous and that loss of physical understanding why the analysis works is risked.

5.4 Improving sensitivity by reducing systematical uncertainties

A further bottleneck limiting the analysis sensitivity are the systematical uncertainties. A possibility to suppress systematical uncertainties, already widely used in the $\mathrm{H}^+ \to \tau\nu_\tau$ searches, is to measure the backgrounds with data-driven methods. Another option to reduce systematical uncertainties is to improve the auxiliary measurements that are used for determining the uncertainties. Such an approach should decrease especially the trigger efficiency measurement, jet energy scale, and b-tagging efficiency uncertainties. Furthermore, systematical uncertainties that are otherwise difficult to suppress, could be constrainable by a fit when statistically combining results of multiple channels. For example, in Ref. [4] the virtue of the otherwise modest di-lepton final state is to constrain the theoretical $\mathrm{t\bar{t}}$ cross section, which is one of the largest uncertainties applied for the signal samples.

6. Summary

The 2012 dataset collected by both the ATLAS and CMS experiments can be expected to contain first signs of light or heavy charged Higgs bosons, should they exist, or otherwise to set limits on the production cross section and branching ratios. The improvement of the light charged Higgs boson searches is challenging, because the analyses are already dominated by systematical uncertainties. On the other hand, the uncertainty of the heavy charged Higgs boson analyses are expected to be statistically dominated and therefore first experimental results for the heavy charged Higgs boson searches become possible with the 2012 dataset in several decay modes.

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