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Systematics in charged Higgs search in ATLAS

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The charged MSSM Higgs boson production via $t \to bH^+$ and the subsequent decay into $H^+ \to c\bar{s}$ or $H^+ \to \tau\nu$ has been studied for the ATLAS experiment, for masses lighter than the top quark mass. The first channel, dominating in the low tanβ region (<1), is explored in the final state with four jets, one lepton and missing energy; the second, at higher tanβ region (>3), is searched in two leptons, two jets and missing energy final state. In both cases, the W boson from the other top quark is required to decay leptonically.

The study has been performed using a realistic detector simulation for the signal and the SM backgrounds. The discovery sensitivity and the upper limit on $\mathscr{B}(t \to bH^+)$ as a function of m_{H^+}, assuming 100% branching ratios of charged Higgs boson either to $H^+ \to c\bar{s}$ or $H^+ \to \tau\nu$, were discussed for different integrated luminosity and center-of-mass energy scenarios: at $\sqrt{s}$ = 10 TeV and $\int \mathscr{L}\,\mathrm{d}t$ = 200 pb^{-1} and at $\sqrt{s}$ = 7 TeV with $\int \mathscr{L}\,\mathrm{d}t$ = 1 fb^{-1}. The results for the lower center-of-mass energy were obtained from those at higher by means of rescaling cross-sections for the relevant processes. The main focus of the present paper is on the impact of systematics on these results.

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1. Introduction

The Minimal Supersymmetric Standard Model (MSSM) is the most investigated extension of the Standard Model (SM). The theory requires two Higgs doublets giving origin to five Higgs bosons: two CP-even neutral scalars, h and H (h is the lighter of the two), one CP-odd neutral scalar, A, and one pair of charged Higgs bosons, $H^{\pm}$. Their discovery would be an irrefutable proof for physics beyond the SM. In particularly, the discovery of the heavier bosons H, A, $H^{\pm}$ is demanded, expecially as the light h may be indistinguishable from a SM Higgs boson. This is a key point in the physics program of future accelerators and in particular of the LHC.

After the conclusion of the LEP program in the year 2000, the experimental limit on the mass of MSSM Higgs charged boson, m_{H^+}[1], was established at about 80 GeV, for most of the representative sets of model parameters. The Tevatron searches complement those performed at LEP covering the tanβ region below 1.5 and above 30 [5]. No evidence of a charged Higgs boson has been found, resulting in limits on the branching ratio, $\mathscr{B}(t \to bH^+)$, the primary production channel.

For phenomenological studies a version of the MSSM, mSUGRA, with fewer parameters is mostly used. At tree level, the MSSM Higgs sector is determined by two independent parameters only; for charged Higgs boson studies these are chosen as m_{H^+} and tanβ, the ratio of the two Higgs doublet vacuum expectations. Radiative correction have a limited effect.

Many signatures of MSSM charged Higgs bosons have been studied for decays into known SM particles in a wide mass range of m_{H^+} in the ATLAS detector at the LHC [1]. The present discussion is limited to the potential for the discovery of light charged MSSM Higgs bosons for masses $m_{H^+} < m_t$ in the channel $H^+ \to c\bar{s}$ in the tanβ <1 region, where the branching ratio is near 40% for m_{H^+} approximatly 130 GeV and in the channel $H^+ \to \tau\nu$ in tanβ >3 region, where the branching ratio exceeds 90%. The $\mathscr{B}(H^+ \to c\bar{s})$ and $\mathscr{B}(H^+ \to \tau\nu)$ are assumed unity, implying that tanβ dependence is not explicit in the present study. The primary H^+ production channel is through top quark decay $t \to bH^+$ and the experimental final state signatures for the decay channels explored are four jets, one lepton and missing energy ($H^+ \to c\bar{s}$), two leptons and two jets and missing energy ($H^+ \to \tau\nu$). A more detailed description of the analysis strategy is given in Refs. [3], [4] and references therein .

The main focus of this paper is on the impact of systematics on the H^+ discovery sensitivity and the branching ratio $t \to bH^+$ upper limit. This issue obviously is deeply connected with the analysis strategy. Therefore, the search strategy and results are briefly discussed for a center of mass energy scenario $\sqrt{s}$=10 TeV with an integrated luminosity $\int \mathscr{L}\,\mathrm{d}t$= 200 pb^{-1}, and the projections at $\sqrt{s}$=7 TeV with an integrated luminosity of $\int \mathscr{L}\,\mathrm{d}t$= 1 fb^{-1} predicted with a rescaling technique, based on cross-section ratios or parton distribution function re-weighting. This latest scenario corresponds to early data expected to be collected by the end of 2011 by the ATLAS experiment.

2. Signal and background

The H^+ search in $t\bar{t}$ pair production has been studied in the decay processes $H^+ \to c\bar{s}$, *semileptonic*, and $H^+ \to \tau\nu \to \ell^+\nu_\tau\bar{\nu}_\tau\nu_\ell$, *dileptonic*. For this purpose, an event sample with full Monte

[1]Charged conjugate states are implied through this note.

Carlo simulation of the experiment (data generation, reconstruction and analysis) is used. Using the branching ratio set by the searches at Tevatron $\mathscr{B}(t \to bH^+)$ [5], the effective cross section $\sigma \times \mathscr{B}(t \to bH^+)$ for the $H^+ \to c\bar{s}$ and $H^+ \to \tau\nu$ channel has been calculated ranging from 29.4 pb to 12.6 pb ($H^+ \to c\bar{s}$) and from 9.3 pb to 7.7 pb ($H^+ \to \tau\nu$).

The main background for $H^+ \to c\bar{s}$ and $H^+ \to \tau\nu$ channels is the production of $t\bar{t}$ events. In fact, the cross section for not fully hadronic (with at least one ℓ) $t\bar{t}$ events is 218.4 pb; and the single top production containing only one lepton is $\sigma_s = 6.6$ pb(s-channel) and $\sigma_t = 124.5$ pb (t-channel). Moreover, W with top quark channel events may have dileptons in the final state ($\sigma_{Wt} = 32.7$ pb). Others backgrounds involving leptonic decays of electroweak gauge bosons have been considered.

2.1 Semileptonic decay: $\mathbf{H^+ \to c\bar{s}}$

This channel considers a $t\bar{t}$ pair decay with one top quark decaying as $t \to bH^+$ followed by a two jet decay of charged Higgs boson, $H^+ \to c\bar{s}$, and the W boson from the second quark decaying leptonicaly. In order to discriminate the signal from backgrounds the following selection criteria are applied: 1) One lepton (e or μ) with transverse momentum $p_T{}^{\ell} > 20$ GeV in the pseudorapidity range $|\eta| < 2.5$; 2) Missing transverse energy E_T^{miss}> 20 GeV; 3) Four jets; $p_T{}^{jet} > 20$ GeV, $|\eta|<$ 2.5. Two of the four leading jets are identified as b-jets.

A charged Higgs boson in the data would appear as a second peak in the reconstructed dijet mass distribution, separated from W. Therefore, the analysis is performed by considering the shapes of the dijet mass distributions. With two identified b-jets, there are four possible combinations of jets with partons and solutions for the longitudinal momentum of the neutrino. A dijet mass fitter is applied to select the most likely jet assignment. This procedure improves the dijet mass resolution [3].

Using the Tevatron upper limits for $\mathscr{B}(t \to bH^+)$ the expect significance $\frac{S}{\sqrt{B}}$, where S and B are the number of signal and background events under H^+ mass peak in a $\pm$ 3 σ window, results to be 5.9, 4.9, 3.3, 4.0 for the m_{H^+} = 90, 110, 130, 150 GeV respectively. A discovery reach is possible only for $m_{H^+} \approx m_W$.

Assuming no charged Higgs boson signal, a binned maximum likelihood method has been used to extract upper limit on $\mathscr{B}(t \to bH^+)$ at 95 % Confidence Level (CL), assuming $\mathscr{B}(H^+ \to c\bar{s})$ = 1. Thousands of simulated pseudo-experiments (PE) have been generated using bin-by-bin Poisson fluctuations in the dijet mass distribution. For each PE, the $\mathscr{B}(t \to bH^+)$ is scanned over the range [0,1] to find the 95% CL positive area of the integrated likelihood. The mean value over all PEs is defined to be the expected limit. Then, the upper limit is extracted as a function of $\mathscr{B}(t \to bH^+)$.

Several quantities used in this analysis to extract $\mathscr{B}(t \to bH^+)$ are subject to experimental systematic uncertainties. Each systematic effect has been evaluated individually using the given uncertainties on an event-by-event basis. These uncertainties are related to the reconstruction of the leptons and the global event activity, such as E_T^{miss} and jet characteristics. The systematic uncertainties affect both selection acceptances and dijet mass shapes, the corner stone of analysis procedure. The main contributions to systematic uncertainties can be identified as: jet energy scale (JES), jet energy resolution (JER), the amount of initial and final state radiation (ISR and FSR) and the choice of Monte Carlo generator (MC). Any other source of systematic affecting both signal and background can be neglected. In this category are uncertainties on: $\sigma_{t\bar{t}}$, luminosity and trigger and reconstruction efficiency. The effect of the b-tag efficiency has been found small for $m_{H^+} \approx m_W$.

The systematic uncertainties is estimated as the change in the upper limit on $\mathscr{B}(t \to bH^+)$ due to a change $\pm 1\sigma$ in each source of systematic error, as [2]. For each source the procedure in extracting the branching ratio upper limit is repeated using a perturbed dijet mass distribution. In addition, the effect of theoretical uncertainties also limits our ability to estimate the signal efficiency. The major theoretical uncertainties concern the choice of MC, evaluated using using another generator(MC@NLO) and the uncertainty on ISR/FSR showering has been evaluated varying PYTHIA ISR/FSR showering on a $t\bar{t}$ sample. The change in acceptance due to JES uncertainty resulted to be an important effect and a calibration procedure has been implemented. This procedure consisted of applying a rescaling factor, obtained from the ratio of the peak positions of dijet mass distribution perturbed by the JES systematic effect and the original. After the recalibration, the analysis is largely insensitive to JES effect. The effects of the experimental uncertainties on the upper limit on $\mathscr{B}(t \to bH^+)$ are summarized in Tab.1 showing as dominant the systematics the jet energy resolution and the b-jet energy scale.

Source	$\mathscr{U}_{\|\eta\| <3.2}$	$\mathscr{U}_{\|\eta\| >3.2}$	$\Delta\mathscr{B}$ [%]	Source	$\mathscr{U}$	$\Delta\mathscr{B}$[%]
Jet Energy Resolution	0.45*$\sqrt{\mathrm{E}}$	0.63*$\sqrt{\mathrm{E}}$	0.71	b-jet Energy scale	$\pm$ 3 %	0.75
Jet Energy scale	$\pm$ 7 %	$\pm$ 15 %	0.07	Lepton Energy scale	$\pm$ 1 %	0.08
MC generator			0.56	ISR/FSR		0.54
Total $\Delta\mathscr{B}(t \to bH^+)$[%]= 1.26%						

Table 1: From left to right: source of systematics, relative uncertainty definition,$\mathscr{U}$ in $|\eta|$ and percentage change on $\mathscr{B}(t \to bH^+)$, $\Delta\mathscr{B}(t \to bH^+)$ for m_{H^+}= 130 GeV due to a $\pm 1\ \sigma$ change .

Table 2 summarizes the expected 95% CL upper limit on $\mathscr{B}(t \to bH^+)$ as function of m_{H^+} mass, considering only statistical error and including the systematic.

m_{H^+}[GeV]	90	110	130	150
$\mathscr{B}(t \to bH^+)$ (stat)	5.8%	3.9%	3.4%	2.3%
$\mathscr{B}(t \to bH^+)$ (stat+sys)	17.8%	5.5%	4.4%	4.3%

Table 2: Expected 95% CL upper limit on $\mathscr{B}(t \to bH^+)$ as function of m_{H^+} from $H^+ \to c\bar{s}$.

The calorimeter response and the reconstruction of the jet energy could be affected by pile-up. A pile-up model, for a luminosity of $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, was used to determine the degradation of the results. At this luminosity, an extra energy is added to each jet shifting the dijet mass distribution to higher mass. Of course, this shift can have a large effect on extracted upper limit of $\mathscr{B}(t \to bH^+)$. A strategy has been developed to take account of this effect, using a jet energy correction (- 920 MeV) per each additional vertex. The degradation in the expected upper limit is between 3% to less than 0.3% as the signal mass increases from 90 GeV to 130 GeV.

2.2 Dileptonic decay: H$^+ \to \tau\nu$

The production advantage of the jet channels is counterbalanced by the difficulty of identifying the hadronic decay of H^+ in pp collisions. In dilepton events, the charged Higgs boson decays as $H^+ \to \ell^+\nu_\tau\bar{\nu}_\tau\nu_\ell$ and the presence of two charged leptons and two b-jets are a clean signature. On

the other hand, the presence of neutrinos escaping the detection makes the reconstruction of invariant mass impossible. Due to various experimental and theoretical uncertainties in early LHC data analysis the discovery of H^+ can't rely on an excess of dileptonic events in $t\bar{t}$ events. Therefore, analysis strategies require the use of discriminating variables to identify between leptons produced in $H^+ \to \ell^+ \nu_\tau \bar{\nu}_\tau \nu_\ell$ from leptons arising from W boson decays. The following variables are chosen as the helicity angle, $\cos\theta^*_\ell$, and generalized transverse mass, $M_{T2}^{H^+}$ [3]. The helicity angle is a function of $p_b \cdot p_l$, the scalar product of b-quark and lepton 4-momenta. The signal events can be selected for the isotropic helicity angle distribution of H^+ decay products.
The following selection criteria have been adopted to select the signal events : 1) Two opposite charged leptons (e or μ) with transverse momentum for the first ${p_{\mathrm{T}}}^{\ell} > 20$ GeV and second largest ${p_{\mathrm{T}}}^{\ell} > 10$ GeV , in the pseudorapidity range $|\eta| < 2.5$; 2) The missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$> 50 GeV; 3) Two jets; ${p_{\mathrm{T}}}^{jet}$ > 15 GeV, $|\eta|$< 5 identified as b-jets; 4) $\cos\theta^*_\ell$ < -0.6 (H^+ side). The $M_{T2}^{H^+}$ provides an additional insight on m_{H^+}, giving an upper bound value, if a signal is observed, but isn't a *a priori* selection.

The Standard Model cross sections at TeV energy are known with large uncertainties. Therefore, the a priory evaluation with Monte Carlo techniques of the background suffers from the same uncertainties. Strategies have been developed on the combined use of Monte Carlo and data to allow a realistic evaluation of backgrounds. For instance, the background normalization factors are determined by isolating each type of background to a unique sideband, that is not sensitive to other processes and determining the normalization factor by the ratio of event numbers between MC samples and data. Another method, using 'tag and probe' approach, has been developed to estimate the portion of $t\bar{t}$ backgrounds due to lepton misidentification.
Using the Tevatron upper limits for $\mathscr{B}(t \to bH^+)$ the expected significance $\frac{S}{\sqrt{B}}$, results to be 8.9, 10.4, 11.7, 11.3 for the m_{H^+} = 90, 110, 130, 150 GeV respectively . This channel appears more promising for a H^+ discovery in all m_{H^+} range considered .

This procedure can be considered essentially as an event counting analysis. Assuming no charged Higgs boson signal, the upper limit on $\mathscr{B}(t \to bH^+)$ is evaluated according to $\mathscr{B} = \frac{N-B}{2\times\sigma_{t\bar{t}}\times\mathscr{L}_{\mathrm{int}}\times\varepsilon_{\mathrm{sig}}}$, where N is the number of observed events with a number of expected background B, $\varepsilon_{\mathrm{sig}}$ is the signal selection efficiency. The upper limit evaluation of $\mathscr{B}(t \to bH^+)$ at 95% CL is based on 1000 toy MC experiments, varying the input parameters by their uncertainties, according to Gaussian distributions. The obtained values are reported in Tab. 3 (second row).

m_{H^+}[GeV]	90	110	130	150
$\mathscr{B}(t \to bH^+)$ (stat)	8.3%	7.1%	7.1%	8.0%
$\mathscr{B}(t \to bH^+)$ (stat+sys)	10.4%	8.9%	8.9%	10.3%

Table 3: Expected 95% CL upper limit on $\mathscr{B}(t \to bH^+)$ as function of m_{H^+} from $H^+ \to \tau\nu$.

Analogously to the previous channel, the impact of systematic uncertainty in the extracted branching ratio has to be evaluated. Since the background samples are normalized to data, many systematic uncertainties actually do not affect the expected number of background events nor the integrated luminosity and the effect on the cross section from signal and background processes is reduced. The uncertainties on normalization, driven by available statistics in both data and

MC samples, are evaluated to be around 7 %. The single top cross section contribute with an additional uncertainty below 1 % to total number of events. The effect of uncertainties on $E_{\mathrm{T}}^{\mathrm{miss}}$ results neglegible. All these uncertainties and their impact to the number of background events and on the selection efficiency are summarized in Tab. 4. Analogously to the semileptonic channel, the effect of theoretical uncertainties has been evaluated. The choice of MC generator, evaluated using another generator (MC@NLO), results imply only minor differences. The uncertainty on ISR/FSR showering has not been included because this event selection does not include a cut on the jet multiplicity.

Source	$\mathscr{U}$ [%]	B [%]	$\Delta\varepsilon_{\mathrm{sig}}$ [%]	Source	$\mathscr{U}$ [%]	B [%]	$\varepsilon_{\mathrm{sig}}$ [%]
Normalization	7	7	-	Trigger	1	<1	1
Lepton ident. eff.	1	<1	1	Lepton fake rate	1	1	1
Lepton energy scale	1	< 1	1	Jet energy scale	7-15 *	7	4
b-tag efficiency	4	< 1	4	b-tag fake rate	10	1	< 1
Total B = 10% , $\Delta\varepsilon_{\mathrm{sig}}$ = 6%							

Table 4: From left to right: source of systematics, assumed relative uncertainty definition,$\mathscr{U}$, and percentage change on number of background events, B, and signal selection efficiency ,$\varepsilon_{\mathrm{sig}}$. *, See Tab.1.

Table 4 summarizes the systematic impact. The impact of pile-up is negligible.

3. Results for $\sqrt{s} = 7$ TeV

At present, the LHC is running at $\sqrt{s}$ = 7 TeV and is planned to accumulate $\int\mathscr{L}\,\mathrm{d}t$= 1 fb^{-1} by the end of next year, 2011. The ATLAS reach in this scenario are derived by detailed analyses at $\sqrt{s}$ = 10 TeV and $\int\mathscr{L}\,\mathrm{d}t$= 10 pb^{-1}. The signal and background cross-sections have been re-scaled to take into account the change in the centre-of-mass energy. The stability of the selection efficiencies against changes in the centre-of-mass has been checked.

The impact of systematic in the measurement of $\mathscr{B}(t \to bH^+)$ based on the semileptonic channel, $H^+ \to c\bar{s}$ is 1.2 % similar to $\sqrt{s}$ = 10 TeV and it is due to the following sources (as Tab.5): Jet Energy Resolution (0.73%), Jet Energy scale (0.04 %), b-jet Energy scale (0.75%), Lepton Energy scale (0.12 %), MC generator (0.47 %), ISR/FSR (0.40 %). The expected 95% CL limit for ATLAS upper limit at $\sqrt{s}$ = 7 TeV ($\int\mathscr{L}\,\mathrm{d}t$= 1 fb^{-1}) on $\mathscr{B}(t \to bH^+)$ as function of m_{H^+} from $H^+ \to c\bar{s}$ and $H^+ \to \tau\nu$ channel, are reported in Tab. 5 and shown in Fig. 1, considering statistical and systematic errors. These limits are substantially better than the current limit at the Tevatron and better of those obtained at $\sqrt{s}$ =10 TeV.

4. Conclusions

The search for a light charged Higgs boson search in ATLAS, using early LHC data, has been reviewed at $\sqrt{s}$ = 10 TeV and $\int\mathscr{L}\,\mathrm{d}t$= 200 pb^{-1} and projected at $\sqrt{s}$ = 7 TeV and $\int\mathscr{L}\,\mathrm{d}t$= 1 fb^{-1}, the expected luminosity collected by the end of 2011. Two channels have been considered: the semileptonic $H^+ \to c\bar{s}$ and dileptonic $H^+ \to \tau\nu$ the current Tevatron limit of $\mathscr{B}(t \to bH^+)$ is expected to be improved already in the early data taking period, but particular attention has to be given to systematic studies.

m_{H^+}[GeV]	90	110	130	150	channel	experiment
$\mathscr{B}(t \to bH^+)$(stat)	4.0%	2.5%	2.3%	1.5%	$H^+ \to c\bar{s}$	ATLAS
$\mathscr{B}(t \to bH^+)$(stat+sys)	14.8%	4.7%	3.4%	3.7%	$H^+ \to c\bar{s}$	ATLAS
$\mathscr{B}(t \to bH^+)$	22%	15 %	8%	13%	$H^+ \to c\bar{s}$	Tevatron
$\mathscr{B}(t \to bH^+)$(stat)	6.5%	5.6%	5.6%	6.6%	$H^+ \to \tau\nu$	ATLAS
$\mathscr{B}(t \to bH^+)$(stat+sys)	8.9%	7.4%	7.7%	8.6%	$H^+ \to \tau\nu$	ATLAS
$\mathscr{B}(t \to bH^+)$	15%	15 %	17%	19%	$H^+ \to \tau\nu$	Tevatron

Table 5: Expected 95% upper limit on $\mathscr{B}(t \to bH^+)$ as function of m_{H^+} mass, as for ATLAS at $\sqrt{s}$= 7 TeV($\int \mathscr{L}\,dt$=1 fb^{-1}), with statistical error(stat) and including systematic error (stat+sys) , for $H^+ \to c\bar{s}$ and $H^+ \to \tau\nu$ channels, assuming $\mathscr{B}(H^+ \to c\bar{s}) = 1$ and $\mathscr{B}(H^+ \to \tau\nu) = 1$. The current Tevatron limit is reported as well.

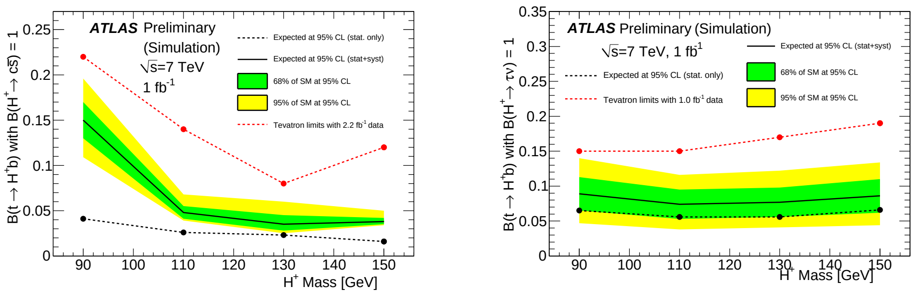

Figure 1: Expected 95%CL upper limit on $\mathscr{B}(t \to bH^+)$ versus H^+ mass from $H^+ \to c\bar{s}$ and $H^+ \to \tau\nu$ channels assuming $\mathscr{B}(H^+ \to c\bar{s})$ = 1 and $\mathscr{B}(H^+ \to \tau\nu)$ = 1 (at $\sqrt{s}$=7 TeV with $\int \mathscr{L}\,dt$= 1 fb^{-1}. The green and yellow bands correspond to the range in which we expect the limit.

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