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CMS CR -2016/177

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

03 August 2016 (v3, 25 August 2016)

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Presented at *DPC-SMF2016 XXX Reunion Anual de la Division de Particulas y Campos de la SMF*

Charged Higgs Analysis in CMS

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Abstract. An overview is given of the possible searches of the Charged Higgs Boson during run 2 of the LHC data taking period. The Charged Higgs boson emerges in several (minimal) Standard Model (SM) extensions such as the 2 Doublet Higgs Model, which predicts 5 physical Higgs bosons, consistent with the SM Higgs boson. Based on the main production and decay modes, the possible intermediate and final state particles are predicted for a Charged Higgs mass higher than the top quark mass ($m_{H^\pm} > m_t$). In particular, the dominant $H^\pm \to \tau\nu$ and $H^\pm \to tb$ channels are discussed in more detail together with their associated background.

1. Introduction to the theory of Charged Higgs bosons

In the Standard Model (SM), gauge invariance requires the (heavy) W and Z gauge bosons to be massless, which is in contradiction with experiment. They acquire mass through the Higgs mechanism, based on spontaneous symmetry breaking of a Higgs doublet

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix},$$

within the Mexican hat shaped potential ($\mu^2 < 0, \lambda > 0$):

$$V(\phi) = \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2.$$

Expanding $V(\phi)$ around its (non-zero) vacuum expectation value $\nu = \sqrt{-\mu^2/\lambda}$, a scalar CP even particle arises in the spectrum of the Lagrangian: the SM Higgs boson. The corresponding Higgs field interacts with the gauge fields giving the corresponding gauge boson mass (except the photon) whereas fermion masses are obtained from Yukawa couplings to this Higgs field.

A simple extension of the SM introduces a second Higgs doublet (ϕ_1, ϕ_2): the 2 doublet Higgs Model (2DHM). Expanding the potential $V(\phi_1, \phi_2)$ around the vacuum expectation values (ν_1 and ν_2 respectively) results in five physical Higgs bosons:

- two neutral CP-even scalars: h (SM Higgs) and H (heavy Higgs);
- two charged Higgs bosons $H^\pm$;
- one neutral CP-odd pseudoscalar A.

The free parameters of the model are the remaining masses of the Higgs bosons and the value of $\tan\beta = \nu_2/\nu_1$. In type-II 2DHM the fermions couple to ϕ_2 for the up quark and to ϕ_1 for the down quark and leptons. The minimal supersymmetric SM is a type II 2DHM.

2. Charged Higgs production and decay

The production of charged Higgs bosons in a pp collider can be distinguished in two mass regions. In the low mass region ($m_{H^\pm} < m_t$), the $H^\pm$ production is mainly through the decay of a top quark to $H^\pm b$ in $t\bar{t}$ production. In the high mass region ($m_{H^\pm} > m_t$), the production of charged Higgs boson is through fusion of top-bottom quarks. Two final states, $H^\pm tb$ or $H^\pm t$ are possible depending whether the 4 or 5 flavor scheme is used (4FS, 5FS).

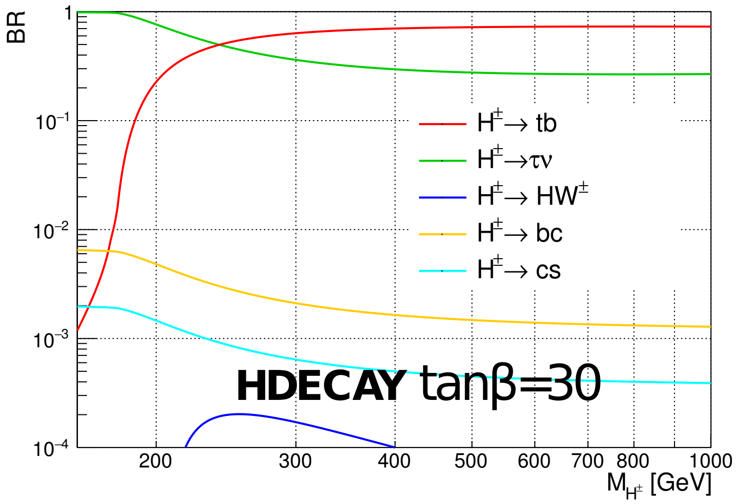

Figure 1. Branching ratios for the main $H^\pm$ decay modes for $\tan\beta = 30$ [3].

The decay of the charged Higgs boson depends mainly on its mass and to a lesser extent on the value of $\tan\beta$. In Figure 1, the most important decay channels with their branching ratios are shown. The most contributing channels in the high mass region are $H^\pm \to \tau\nu$ and $H^\pm \to tb$. Currently the analysis in CMS is focused on those channels, yet the $H^\pm \to hW$ and more exotic channels (e.g. $H^\pm \to$ SUSY, $H^\pm \to AW$ with A the neutral CP-odd pseudoscalar particle) are also under investigation. The channels $H^\pm \to cb, cs$ are more important in the low mass region and are also under investigation.

In the Compact Muon Solenoid (CMS) collaboration [1] the current searches for charged Higgs signals are both focussed on light and heavy Charged Higgs particles, involving all the channels as mentioned above as well as the $H^\pm \to WZ$ channel. Here only the $H^\pm \to \tau\nu$ and $H^\pm \to tb$ channels will be briefly discussed.

3. The $H^\pm \to \tau\nu$ channel

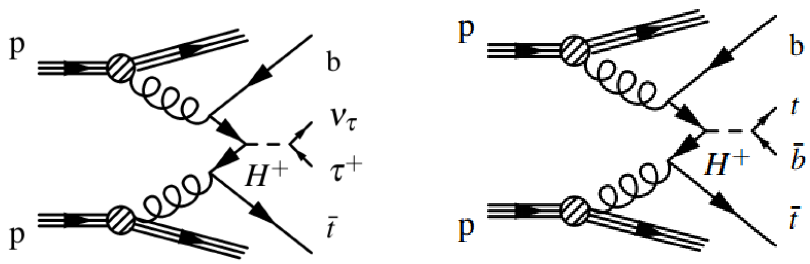

Figure 2. Feynman diagrams for the two dominant charged Higgs decay mode channels $H^\pm \to \tau\nu$ (left) and $H^\pm \to tb$ (right).

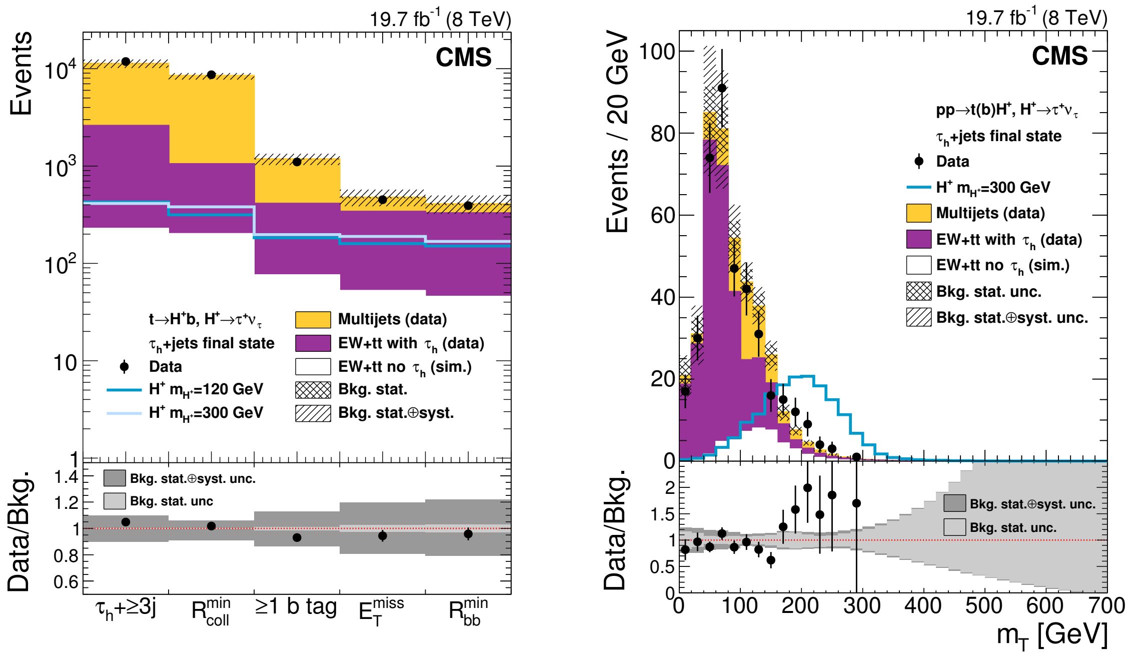

Figure 3. Left: Cutflow diagram for event selection of the $H^{\pm} \rightarrow \tau\nu$ channel. Right: invariant transverse mass distribution after event selection based on the leading τ and MET [2].

This channel is characterized with the $t(b)\tau\nu$ as semi-final state particles. The neutrino will be assigned as missing transverse energy (MET) whereas the τ can decay leptonically (35 %) or hadronically (65%) involving (charged) pions [4]. The decay of the top quark results in W+b-jet, where the W can again decay leptonically or hadronically producing jets. The main background events are multijets (QCD), dibosons (WW, WZ, ZZ), W+jets and $t\bar{t}$.

When restricting to hadronic decay modes (both for the W and the τ), the 2 neutrinos originates only from the charged Higgs and the transverse mass m_T can be reconstructed based on the leading τ (highest p_T) and MET. A shape analysis performed on the m_T distribution will be used to separate the signal from background events.

The analysis strategy is based on the 8 TeV experience [2]. Event cuts are applied on the final-state particles based on the required event topology as described above and additional cuts for background suppression:

- at least 1 τ, $p_T > 51$ GeV, $|\eta| < 2.1$;
- no (isolated) leptons;
- large MET > 130 GeV;
- at least 3 jets, one b-jet;
- angular cuts $R^{min}_{coll,bb}$ for multijet suppression.

The QCD multijet contribution is estimated via a τ_h-misidentification rate technique based on events passing up to the one b-jet requirement whereas the EWK+$t\bar{t}$ background is obtained by using an embedded technique using μ+jets events. The event cut-flow diagram for the 2014 data taking with $\sqrt{s} = 8$ TeV is shown in Figure 3 (left). After passing the full selection criteria, the invariant mass based on the leading τ and MET is calculated and is shown in Figure 3 (right). A signal sample with $m_{H^{\pm}} = 300$ GeV is superimposed for illustrative purposes.

For the $\sqrt{s} = 13$ TeV analysis the selection criteria will be optimized and refined based on the ratio $S/\sqrt{B}$ by varying the cut boundaries or by categorization of the events (e.g. on b-jets). The dominant backgrounds will be estimated based on data-driven techniques using events in control regions.

4. The $H^{\pm} \to tb$ channel

For this channel the semi-final state particles are $tt(b)b$. The top quarks will decay into W+b-jets, yielding at least 3 b-jets in the final state. Both W bosons can decay leptonically or hadronically. Current analysises in CMS are focused on one- or two-leptonic final states by selecting on a specific lepton trigger. To distinguish signal from background the scalar sum of jet transverse energies distribution H_T is used. The full hadronic final state (no leptons) is characterized by a high jet multiplicity: two jets for each W, and at least 3 b-jets. Therefore in the hadronic final state the b-jet multiplicity distribution is also used to distinguish the signal from background. The dominant backgrounds are W+jets, $t\bar{t}$, single t and QCD multijets. Dibosons, $Z/\gamma*$+jets and $t\bar{t} + W/Z$ have less contribution to the background.

The search strategy for the $H^{\pm} \to tb$ channel is also based on the 8 TeV experience [2]. Cuts are applied based on the amount of leptons, lepton p_T, MET and jet multiplicity. For the leptonic final states, the event spectrum is divided into different regions based on the amount of jets, both for muons and electrons:

- Control region ($2 \leq N_{jet} \leq 3$): low jet multiplicity used to derive background normalizations;
- Signal region ($N_{jet} \leq 4$): high jet multiplicity consistent with the signal signature.

Each region is further classified in the b-tag multiplicity, ranging from 0, 1 and ≥ 2 b-jets for the control region and 1, ≥ 2 b-jets for the signal region. For each signal region, the H_T distribution is obtained and the signal is compared to the background.

5. Results and conclusions

In the high mass region of the charged Higgs, the dominant channels are $H^{\pm} \to \tau\nu$ and $H^{\pm} \to tb$. Within the CMS collaboration, these channels are currently being investigated with the 13 TeV data as well as other channels in the low mass region and some more exotic channels. Several cuts are applied for background suppression based on the 8 TeV experience and the signal is distinguished from background based on the m_T, H_T and b-jet multiplicity distributions. For the 8 TeV analysis, a combined statistical analysis has been performed in the high mass region ($180 < m_{H^{\pm}} < 600$ GeV). The data agree with the SM prediction and upper limits of the Charged Higgs have been set, including systematic uncertainties.

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