Search for light charged Higgs bosons with the $H^{\pm} \to \tau^{\pm}\nu_{\tau}$ decay in the fully hadronic final state

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1. Motivation

In the Minimal Supersymmetric Standard Model (MSSM), there are five Higgs scalar mass eigenstates; two $\mathcal{CP}$-even h^0 and H^0, one $\mathcal{CP}$-odd A^0, and two electrically charged $H^{\pm}$. At tree-level, the Higgs-related parameters are determined by the ratio of the vacuum expectation values of the two Higgs boson doublets $\tan\beta = \frac{v2}{v1}$ $(0 \leq \beta \leq \frac{\pi}{2})$, and one of the Higgs boson masses. The dominant production for light charged Higgs bosons at the LHC is through $t \to bH^{\pm}+X$, with the cross-section shown in Fig. 1 (a) for several $\tan\beta$ values. As shown in Fig. 1 (b), for small values of $m_{H^{\pm}}$ the decays of $H^{\pm}$ proceed almost exclusively through the process $H^{\pm} \to \tau^{\pm}\nu_{\tau}$ with $BR(H^{\pm} \to \tau^{\pm}\nu_{\tau}) \approx 1$. The present work, documented in Ref. [1], is concerned with the fully hadronic final state of $t\bar{t} \to bW^{\pm}bH^{\mp}$ and $t\bar{t} \to bH^{\pm}bW^{\mp}$ events, where the τ-lepton decays to hadrons (τ jet) and the associated $W^{\pm}$ decays to quark pairs. In this channel a visible signal can be obtained in the transverse mass reconstructed from the τ jet and missing E_T originating from $H^{\pm}$ decays.

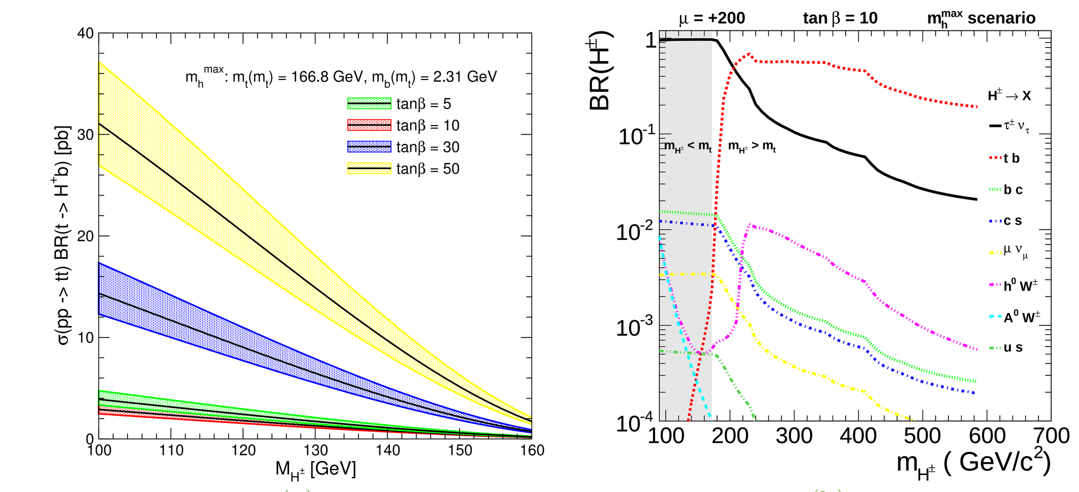

Figure 1: (a) Production cross-section for $H^{\pm}$ at $\sqrt{s} = 7$ TeV with $\sigma_{t\bar{t}} = 164.57$ pb [2] and (b) branching ratio of $H^{\pm}$ as a function of its mass [3].

2. Signal & Backgrounds

The signal final state $qqb\bar{b}\tau^{\pm}\nu_{\tau}\bar{\nu}_{\tau}$ is characterised by the presence of:

- two hadronic jets from $W^{\pm}$ decays
- two b-jets from $t \to bH^{\pm}$ ($\bar{t} \to \bar{b}W^{-}$) decays
- one τ jet from $H^{\pm} \to \tau^{\pm}\nu_{\tau}$ decays
- missing transverse energy (E_T^{miss}) due to presence of neutrinos

The main background is comprised of QCD multijet production, Standard Model (SM) $t\bar{t}$ and W + jets events. In addition, the single-top, di-boson (WW, WZ, ZZ) and Drell-Yan ($Z/\gamma^* \to \ell\ell$) production processes also have small contributions to the total background.

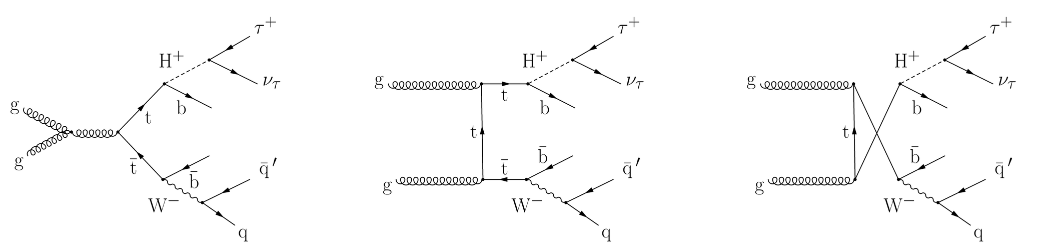

Figure 2: Dominant Feynman diagrams ($\sim 87\%$) for the $t\bar{t} \to bH^{\pm}bW^{\mp}$ signal production at the LHC, in the (a) s-channel, the (b) t-channel and the (c) u-channel.

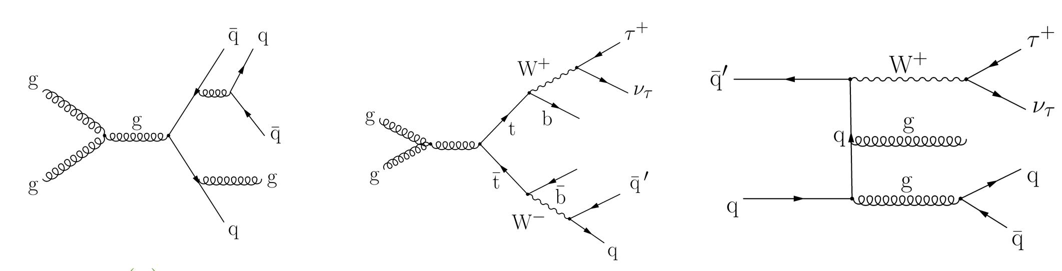

Figure 3: Feynman diagrams for the background processes of (a) QCD multijet, (b) SM $t\bar{t}$, and (c) W + jets.

3. Background Suppression

The main challenge is to suppress the large QCD multijet background, which can mimic the signal due to fake E_T^{miss} and hadronic jets faking the signature of τ jets. In order to suppress this dominant background, the presence of a tightly isolated 1-prong τ-jet and large E_T^{miss} was required to be present in the selected events. The W + jets background can be efficiently suppressed by requiring at least one jet to be b-tagged, but the SM $t\bar{t}$ and single-top backgrounds are largely irreducible. Nevertheless, it is possible to suppress to some degree the SM $t\bar{t}$ background by exploiting the τ-helicity correlations [4, 5]. The method relies on the fact that, since $H^{\pm}$ is a scalar particle and since only left-handed (right-handed) neutrinos (anti-neutrinos) exist in nature, the τ-lepton in the $H^{+} \to \tau^{+}\nu_{\tau}$ decay is produced left-handed, as shown in Fig. 4 (a). On the contrary, in the $W^{+} \to \tau^{+}\nu_{\tau}$ decay, the τ-lepton emerges right-handed due to the vector nature of the $W^{\pm}$ boson, as shown in Fig. 4 (b). These correlations lead to harder leading charged hadron from the $H^{\pm}$ decay than from the $W^{\pm}$ decay in the backgrounds, and can be exploited by the use of the $R_{\tau} = p^{\text{ldg. charged particle}}/p^{\tau\text{ jet}}$ variable.

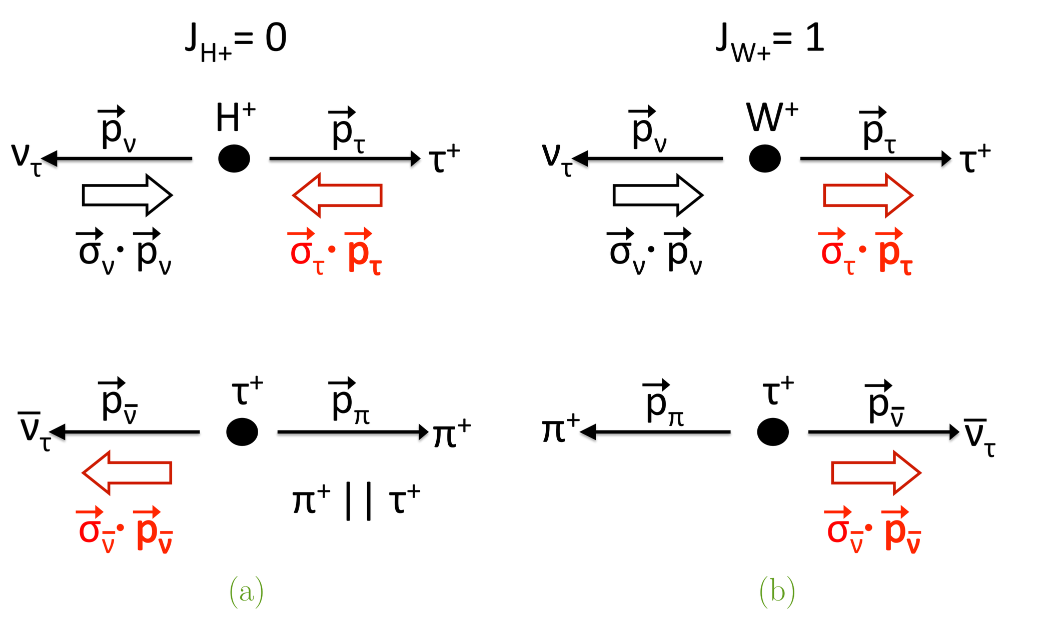

Figure 4: The τ-helicity correlations in $\tau^{+} \to \pi^{+}\bar{\nu}_{\tau}$ decays.

4. Signal Selection

The candidate signal events were triggered with a single τ jet + E_T^{miss} trigger. The offline signal selection can be summarised as follows:

- One tightly isolated τ jet with $p_T > 40\,\text{GeV}/c$, $|\eta| < 2.1$, $R_{\tau} > 0.7$
- Veto on isolated electrons/muons with $p_T > 15\,\text{GeV}/c$, $|\eta| < 2.5$
- At least 3 hadronic jets with $p_T > 30\,\text{GeV}/c$, $|\eta| < 2.4$
- Large missing E_T with $E_T^{miss} > 50\,\text{GeV}$
- At least 1 hadronic jet successfully b-tagged (high efficiency, low purity)
- Requirement that $\Delta\phi\left(\tau \text{ jet}, E_T^{miss}\right) < 160°$

The distributions of E_T^{miss} and $\Delta\phi\left(\tau \text{ jet}, E_T^{miss}\right)$ are shown in Fig. 5, with the expected event yield in the presence of the $t \to bH^{\pm}$, $H^{\pm} \to \tau^{\pm}\nu_{\tau}$ decays shown as a dashed red line, for $m_{H^{\pm}} = 120\,\text{GeV}/c^2$ and assuming $BR(t \to bH^{\pm}) = 0.05$ and $BR(H^{\pm} \to \tau^{\pm}\nu_{\tau}) = 1$.

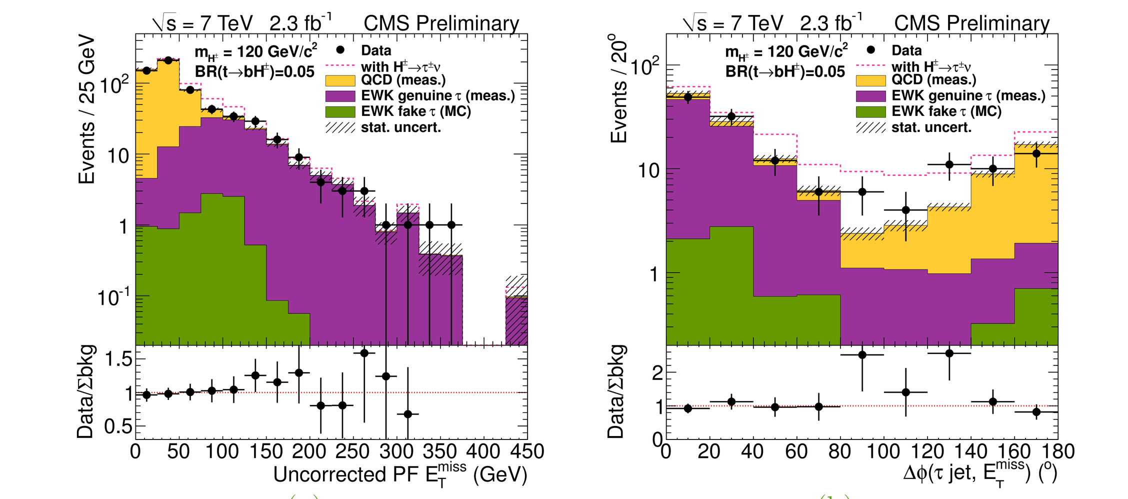

Figure 5: (a) Distribution of E_T^{miss} after τ-jet identification, lepton veto, and hadronic jets selection. (b) Distribution of $\Delta\phi\left(\tau \text{ jet}, E_T^{miss}\right)$ after all signal selections.

5a. QCD Multijet Background Measurement

The QCD multijet background was measured with data-driven techniques, exploiting the fact that the events triggered with the single τ jet + E_T^{miss} trigger are strongly dominated with the QCD multijet production. The methodology employed relied on factorisation techniques, whereby key selections of the analysis where removed from the cut-flow and re-introduced in the form of efficiencies. The selection steps are shown in Fig. 6.

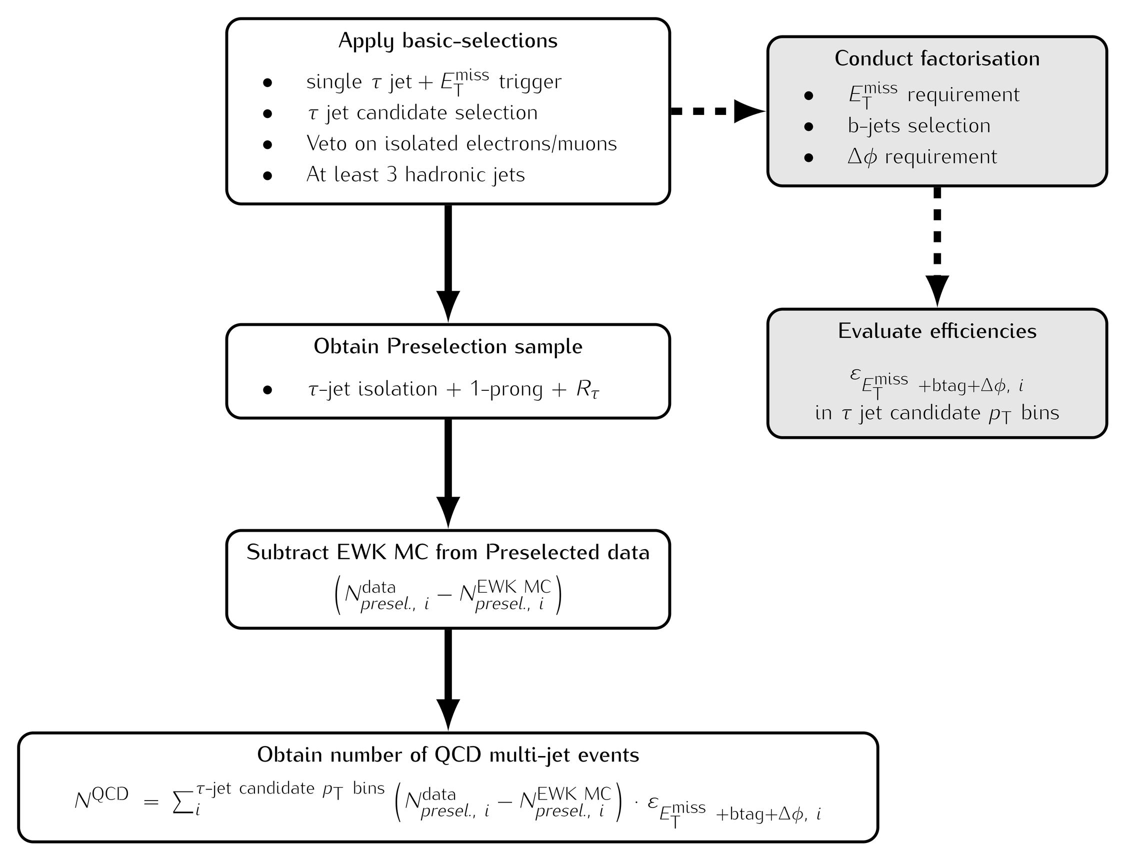

Figure 6: Schematic overview of the QCD multijet background measurement.

5b. EWK+$t\bar{t}$ Genuine Tau Background Measurement

The SM $t\bar{t}$, W + jets, single-top and other electroweak (EWK) backgrounds with genuine τ jets were measured from events triggered with single muons. The muon was transformed to a simulated τ-lepton with the "Tau embedding method" [6, 7, 8], resulting in a very realistic *hybrid* event. By applying the signal selections and correctly normalising the control sample, an estimate for the number of electroweak backgrounds with genuine τ jets was obtained. The selection steps are shown in Fig. 7.

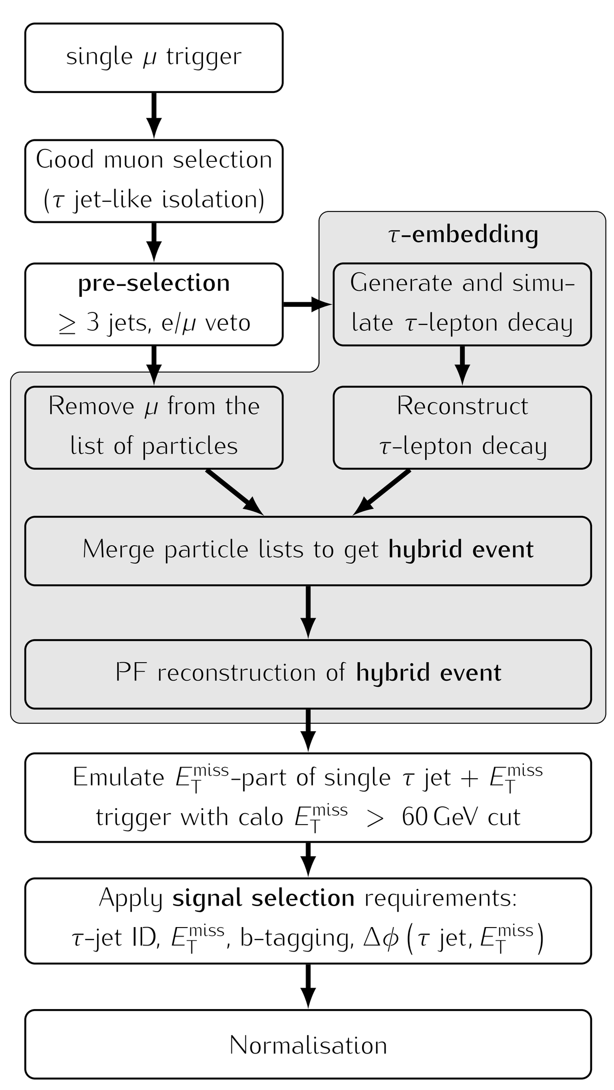

Figure 7: Schematic overview of the EWK+$t\bar{t}$ genuine tau background measurement.

6. Summary of Results

The number of events from the data, the measured backgrounds and the expected signal for $m_{H^{\pm}} = 120\,\text{GeV}/c^2$ and $BR(t \to bH^{\pm}) = 0.05$, are shown in Table 1. The corresponding number of events as a function of the selection steps in shown in Fig. 8 (a), while the transverse mass distribution after all selections is shown in Fig. 8 (b).

Table 1: Summary of the expected and observed event yields, for 2.3 fb^{-1} of data.

Process	Events	Statistical	Systematic
$H^{\pm}H^{\mp} + H^{\pm}W^{\mp}$	51	± 4	± 8
EWK+$t\bar{t}$ genuine tau (data-driven)	85.8	± 3.6	± 11.2
QCD multijet (data-driven)	26	± 2	± 1
EWK+$t\bar{t}$ fake τ (simulation)	6.4	± 3.1	± 3.3
Expected from SM	119	± 5	± 12
Observed in data	130		

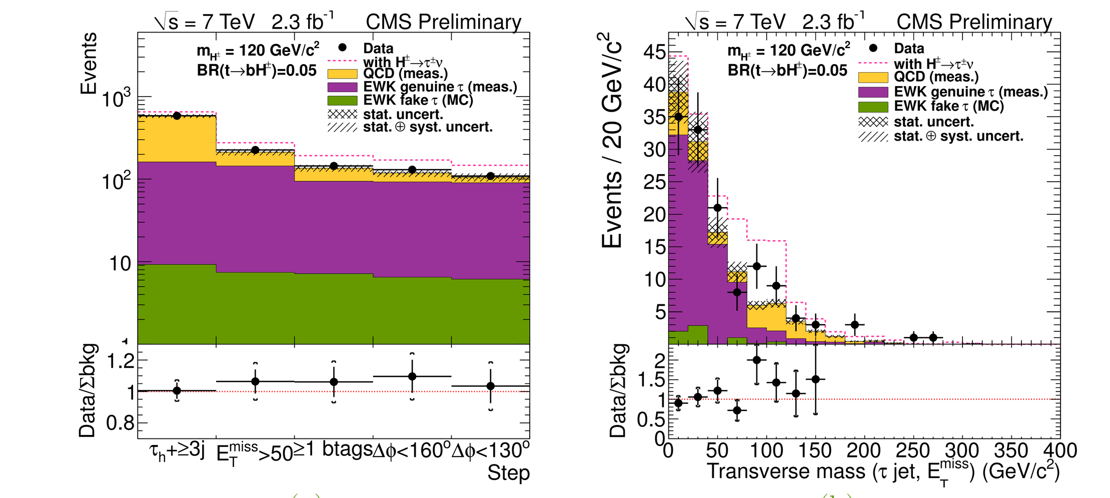

Figure 8: (a) Number of events after every selection step, starting from the hadronic jet selection. (b) The transverse mass distribution, after all selections.

7. Exclusion Limits

To assess the degree of compatibility of the observed data with the signal-hypothesis, the light charged Higgs transverse mass $m_T(\tau \text{ jet}, E_T^{miss})$ was employed in a CLs binned maximum likelihood fit. The observed and expected model-independent upper limits determined for $BR(t \to bH^{\pm})$ were found to be $2 - 7.3\%$ and $1.5 - 5.2\%$, respectively, for the mass range $80\,\text{GeV}/c^2 \leq m_{H^{\pm}} \leq 160\,\text{GeV}/c^2$ and as shown in Fig. 9 (a). These limits were transformed to the $(\tan\beta, m_{H^{\pm}})$ plane of the MSSM maximal mixing scenario (m_h^{max}), as shown in Fig. 9 (b), and were found to exclude a significant region, that had previously remained unexplored.

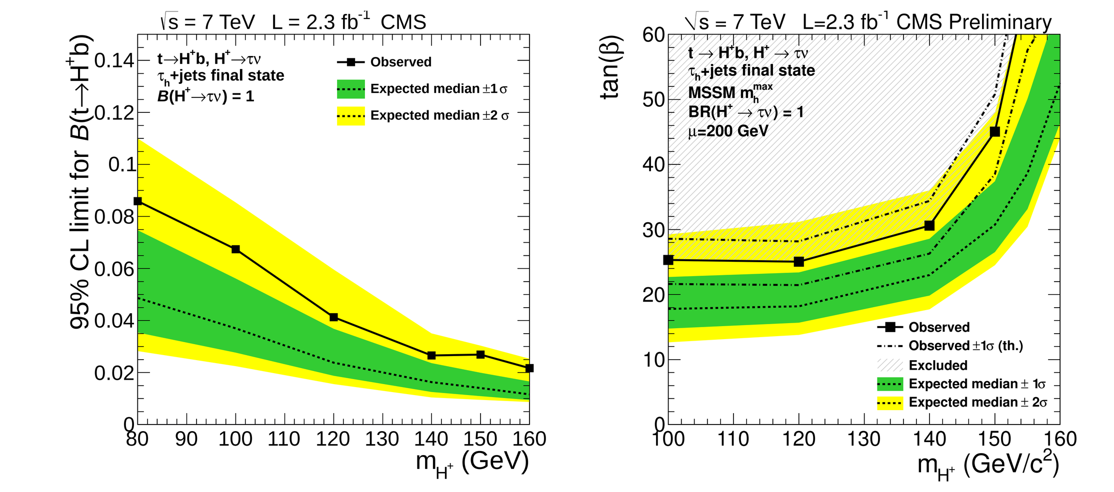

Figure 9: (a) Model-independent upper limits on $BR(t \to bH^{\pm})$, for the $H^{\pm}$ mass hypotheses in the 80–160 GeV/c^2 region and assuming $BR(H^{\pm} \to \tau^{\pm}\nu_{\tau}) = 1$. (b) The exclusion region in the $(\tan\beta, m_{H^{\pm}})$ plane of the MSSM m_h^{max} scenario ($\mu = 200$ GeV).

The CMS collaboration has also conducted analyses on additional final states, all requiring the presence of a τ-lepton from the $H^{\pm}$ decay, missing transverse energy and multiple jets; the ***semi-leptonic*** final state with the τ-lepton decaying hadronically and an electron or a muon from the associated $W^{\pm}$ decay, and the ***di-lepton*** final state with an electron and a muon. The combination of all final states has yielded upper limits on $BR(t \to bH^{\pm})$ in the range of 2–3%, in the 80–160 GeV/c^2 region.

8. References

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