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Improved sensitivity to charged Higgs searches un top quark decays $t \to bH^+ \to b(\tau^+\nu_\tau)$ at the LHC using τ polarisation and multivariate techniques

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We present an analysis with improved sensitivity to the light ($m_H \leq m_t - m_b$) charged Higgs searches in the top quark decays $t \to bH^+ \to b(\tau^+\nu_\tau) + c.c.$ in the $t\bar{t}$ and single top production processes at the LHC. We note that the τ^+ arising from the H^+ (W^+) decay are predominantly right (resp. left) hand polarized. We focus on the dominant hadronic one-prong decay $\tau^\pm \to \rho^\pm\nu_\tau \to \pi^\pm\pi^0\nu_\tau$. We use distributions as the fractional energy of the charged pion track with respect to the total τ-jet energy and the cosine of the helicity angle ψ to feed and train a BDT classifier within TMVA to separate the signal for H^+ production from the dominant SM background.

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1. Theoretical background

The Higgs sector of the Minimal Supersymmetric Standard Model (MSSM) is composed of two Higgs doublets, Φ_u, Φ_d with different vacuum expectation values, v_u, v_d respectively, which are related by $\tan\beta = v_u/v_d$. This leads to five different Higgs particles, namely A^0, h^0, H^0 and $H^\pm$. On this work, we focus on the last ones, $H^\pm$, which can be produced at the LHC via the top quark decays $t \to H^+ b$. The relevant part of the interaction Lagrangian can be written as:

$$\mathscr{L}_{H^+} = \frac{g}{\sqrt{2}M_W} H^+ \left[\cot\beta V_{ij} m_{u_i} \bar{u}_i P_L d_j + \tan\beta V_{ij} m_{d_j} \bar{u}_i P_R d_j + \tan\beta m_{l_j} \bar{\nu}_j P_R l_j\right] + h.c. \tag{1.1}$$

Where V_{ij} are the CKM flavour mixing matrix elements. If we focus on the leptonic term, we see that H^+ couples to right-handed leptons, whereas in the Standard Model (SM), the W bosons couple to the leptons via the charged current interaction Lagrangian, which involves only left-handed leptons:

$$\mathscr{L}_{CC} = \frac{g}{\sqrt{2}M_W} W_\mu^+ \left[\bar{\nu}_j \gamma^\mu P_L l_j + V_{ij} \bar{u}_i \gamma^\mu P_L d_j\right] + h.c. \tag{1.2}$$

Where P_L and P_R are the left-right chirality operators, defined as $P_{R,L} = \frac{1}{2}(1 \pm \gamma_5)$. These differences on the couplings lead to different angular distributions of the τ decay products, which will be exploited on our analysis.

2. Relevant observables

We consider the process $pp \to t\bar{t}$ where both top quarks decay via Wb. The electron or muon coming from the leptonic W^- decays are used for triggering purposes. The W^+ is left to decay into a $\tau^+\nu_\tau$. This is our irreducible background process. Our signal proceeds when the $t \to bH^+$. The signal and background events for top pair and single top production have been generated using Pythia 6.4 and they are required to pass standard acceptance and trigger cuts, [1]. See figure 1 for the relevant Feynman diagrams and [2] for recent analysis exploring this channel.

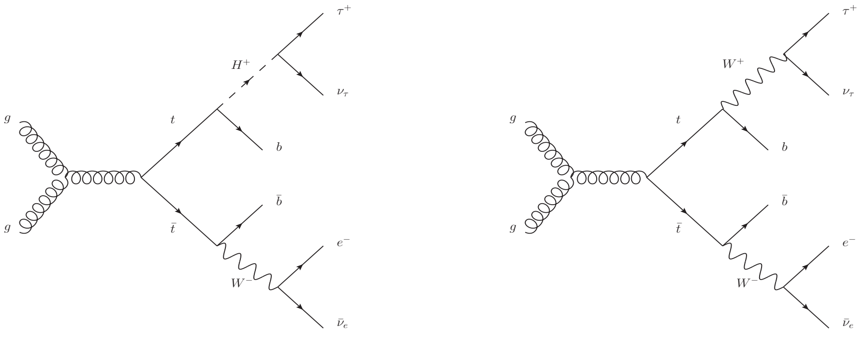

Figure 1: Signal and SM irreducible background processes for $t \to H^+ b$

2.1 Helicity angle ψ

The helicity angle is defined as the angle between the outgoing direction of the top quark and the ρ meson in the reference frame where the W boson (or the H^+ in our case) is at rest. It can be aproximated by the following expression:

$$\cos\psi = -\frac{\vec{p}_t \cdot \vec{p}_\rho}{|\vec{p}_t||\vec{p}_\rho|} \simeq \frac{2m_{\rho b}^2}{m_t^2 - m_W^2} - 1 \tag{2.1}$$

The distributions for $\cos\psi$ for H^+ masses of 90, 110, 130 and 150 GeV, as well as for the SM background $t \rightarrow W^+ b$ are shown in figure 2

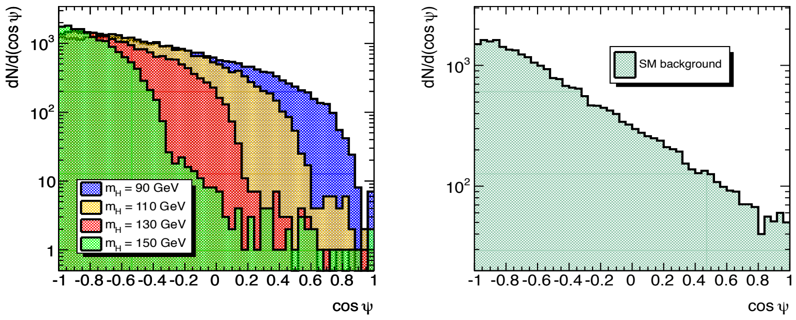

Figure 2: $\cos\psi$ for different H^+ masses and the SM background

2.2 τ energy ratio

In this study, we only allow τ leptons to decay via the 1-prong channel $\tau \rightarrow \rho\nu_\tau \rightarrow \pi^+\pi^0\nu_\tau$. Thus, another observable which could help in the classification of H^+ events is the energy and p_T of the charged pion normalized to those of the τ-jet i.e.

$$\lambda_e = \frac{E_\pi}{E_\rho}; \quad \lambda_p = \frac{p_T^\pi}{p_T^\rho} \tag{2.2}$$

The distributions for these variables are shown in figure 3

2.3 τ-jet energy ratio to b-jet energy

As the H^+ in this study is heavier than the W, τ-jets coming from massive Higgs bosons are harder than τ-jets coming from W bosons. On the other hand, the b-jets coming from the W^+ production vertex are harder than the ones coming from H^+ vertices. Therefore, a good discriminating variable would be the ratio from the τ-jet energy and p_T to the corresponding b-jet kinematical quantity. The distributions are shown in the right part of figure 3. The identification of this b-jet (there are two in every event) could be done using topological correlations between the H^+ decay products (the τ-jet) with respect to the b-jet, either in $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ between the b-jet from the H^+ production vertex and the τ-jet from the H^+ decay, or else using the fact that this b-jet has opposite charge to the charged pion from the τ decay.

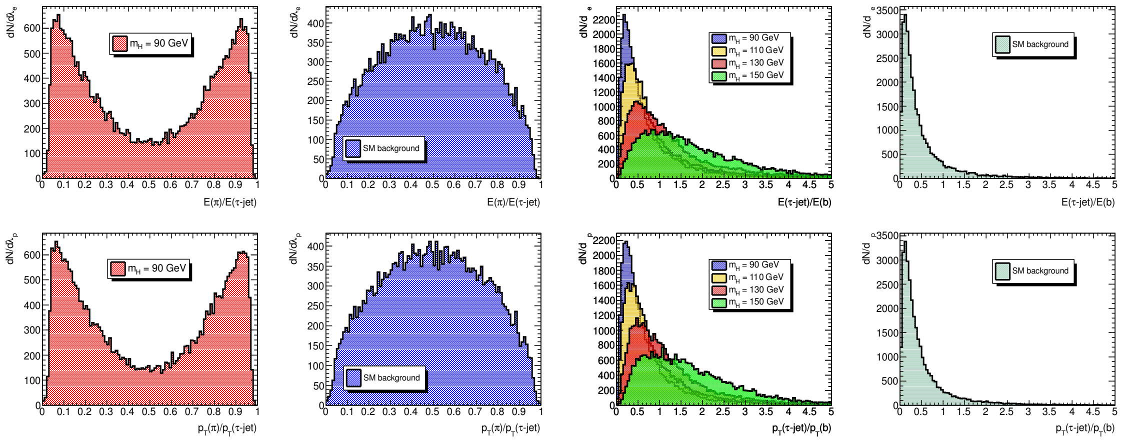

Figure 3: Energy and momentum ratio from the pion to the τ-jet. Ratio τ to b energy and p_T

3. H^+ production in the single top channel

The single top channel has the advantage that the mass of the charged Higgs boson can be measured. We define the W transverse mass as

$$m_T^W = \sqrt{2p_T^\tau E_T^{miss}(1-\cos\Delta\phi)} \tag{3.1}$$

This variable gives a good discrimination between signal and background, but does not help to measure the actual H^+ mass. To this purpose, we define (see [6])

$$(m_T^H)^2 = \left(\sqrt{m_t^2 + (\vec{p_T}^{\,l} + \vec{p_T}^{\,b} + \vec{p_T}^{\,miss})^2} - p_T^b\right)^2 - (\vec{p_T}^{\,l} + \vec{p_T}^{\,miss})^2 \tag{3.2}$$

The distributions for the variables defined in equations 3.1 and 3.2 are shown in figure 4

4. TMVA results

Once we have these variables simulated for the signal and background processes, we use them to train a Boosted Decision Tree (BDTD) in order to obtain the best separation between the signal and background processes. The classification of a given event would be done attending to these distributions. We do this separately for the $t\bar{t}$ and single top processes.

4.1 Top pair production

For the $t\bar{t}$ channel, TMVA provides a good discrimination between processes mediated by H and W charged bosons. Figure 5 shows the BDTD output distributions for the signal and background processes in this channel (left) as well as the ROC curves, efficiency versus background rejection (right). For the less favorable case ($m_H = 90$ GeV), a background rejection of 90% can be achieved with a 50% signal efficiency. Considering the less preferred case $\tan\beta = 10$ for which $\mathscr{B}(t \to H^+ b) \simeq 0.02$ (see [7]) and taking into account the fact that for a center of mass energy of

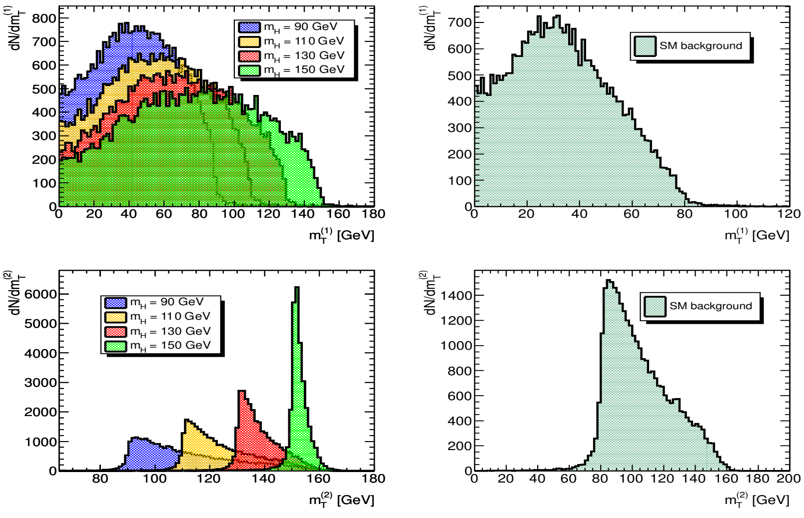

Figure 4: Transverse masses for the W and charged Higgs

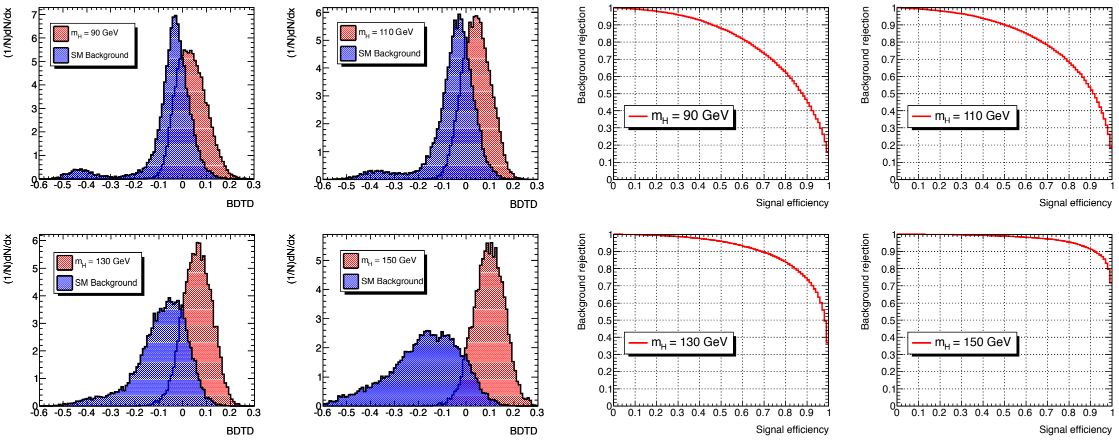

Figure 5: BDTD outputs for the $t\bar{t}$ channel

$\sqrt{s} = 14$ TeV the $t\bar{t}$ cross section is $\sigma_{t\bar{t}} \simeq 874$ pb, with an integrated luminosity of 10 fb^{-1}, one will get $2 \cdot 10^4$ (10^5) signal (resp. background) events. The production via the two possible charge conjugate final states has been taken into account . The expected significance therefore would be:

$$S = \frac{N_{signal}}{\sqrt{N_{background}}} \simeq \frac{10^4}{\sqrt{10^4}} = 100$$

This will be reduced by a factor of 3 when including efficiencies for trigger, $b - jet$ tagging and τ identification. For a center of mass energy of $\sqrt{s} = 7$ TeV, the cross sections are reduced by a factor of 4, so that our expected significance will be reduced by an additional factor of 2.

4.2 Single top production

The single top channel achieves an even better discrimination, as the mass distributions provide an additional handle for the separation between the two processes. Figure 6 shows the BDTD outputs for each mass (left) and the ROC curves (right).

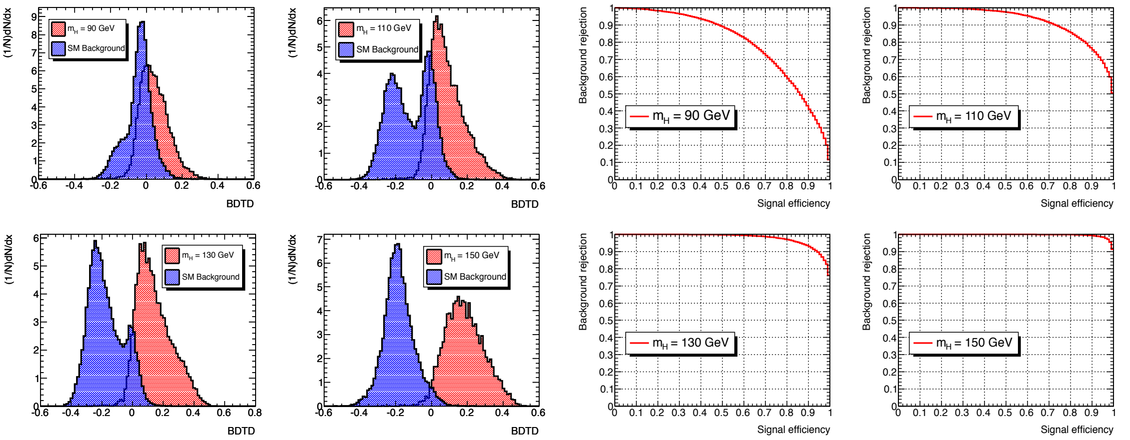

Figure 6: BDTD outputs for the single top channel

A similar calculation for the single top channel ($\sigma \simeq 200$ pb at $\sqrt{s} = 14$ TeV) yields a significance of $S \simeq 85$, which will be reduced by trigger and acceptance cuts as discussed above.
To summarize, we believe that if a light H^+ as expected in the MSSM exists, we will not miss it, by looking at the one prong hadronic τ decays, for any value of $\tan\beta$.

5. Acknowledgements

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