Top physics beyond the standard model: Prospects at CMS

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Summary. — Precise studies of the top-quark sector will be performed in the LHC in order to test the standard model and search for new physics. The top-quark sector at the LHC opens a very rich region to look for new phenomena. Searches beyond the standard model include new top quark decays and top quarks in resonant production. In the latter, a good observable to carry on a model-independent search is the top pair invariant mass. A special reconstruction procedure is needed for the case of heavy resonances decaying into very high-p_T top jets. CMS is developing tools to improve the reconstruction of these highly boosted top jets and studying the discovery potential for new physics in the top quark sector. A brief review of these studies is given in this note.

PACS `14.65Ha` – top quarks..

1. – Introduction

Precision top-quark physics will be carried on by the LHC experiments thanks to production of a much larger data set than the current Tevatron top-quark sample. At the design luminosity of 10^{-34} cm^{-2}s^{-1}, the LHC will produce about 80 million top pairs and 40 million single top events per year. The large statistics top event sample opens the possibility to use top quark events as a tool to calibrate the detector. For example, top quark events can be used to measure the absolute jet energy scale and the b-tagging efficiency. Besides testing the standard model (SM) and using top events as a standard candle, top physics opens a rich region for searches beyond the standard model (BSM). Because of the large top Yukawa coupling, we expect new physics to have strong couplings to the top sector [1]. New phenomena in the top-quark sector can appear as new decay channels or top quarks in resonant production [2].

The top quark has a special role both in the standard model and BSM. Within the SM, the top quark is naturally related to the electroweak (EWK) symmetry breaking (EWSB) because of its large Yukawa coupling to the SM Higgs, and because the top mass is at the EWK scale. In addition, the top-quark loop presents the largest contribution to the quadratic divergence of the SM Higgs mass. Because of its prompt decay, it offers the possibility to study properties of a bare quark, *e.g.* spin, mass, and coupling. Within BSM models, there are many alternative mechanisms of EWSB, *e.g* models with

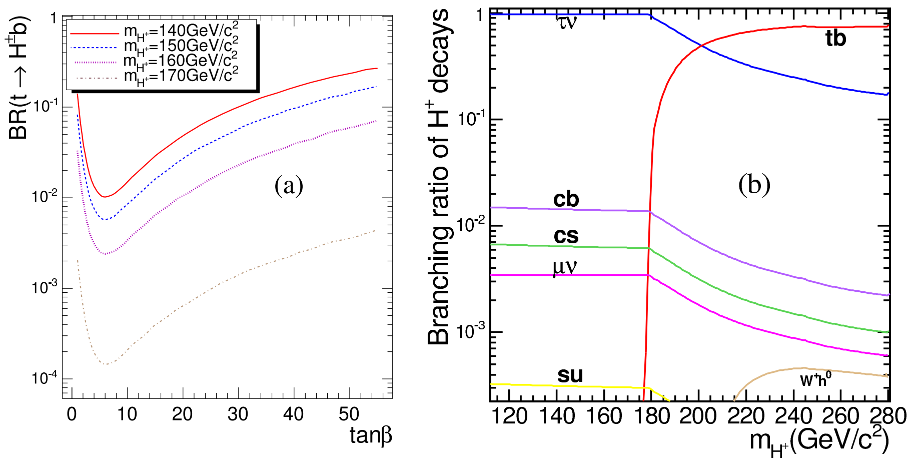

Fig. 1. – (a) Branching ratio of $t \to H^{\pm}b$ vs $\tan\beta$, and (b) branching ratios for charged Higgs boson decaying to different final states for $\tan\beta = 20$.

top partners in order to compensate for the large top radiative correction to the Higgs mass (SUSY, Little Higgs, Extra Dimensions). The large top mass opens up a large phase space for decays to heavy states. There are models where couplings of new gauge interactions to the top quark are enhanced. In such models new particles could show up as resonances which decay to $t\bar{t}$.

In this note, we summarize the results of exploring the discovery potential in the top sector with the CMS detector. A detail description of the CMS detector can be found somewhere else [3]. We concentrate on searches for new top decays and the search for heavy resonances into $t\bar{t}$ decays. Studies about the search for top partners and other exotic top searches are currently being done in CMS.

2. – Top quark decays

In the SM, flavor changing neutral currents (FCNC) are suppressed by the GIM mechanism. The dominant decay channels are through the weak charged-currents (CC). Because of $V_{tb} >> V_{td}, V_{ts}$ [4], the predominant top decay channel is to a b quark. In addition, the top quark has a prompt decay via the first order weak interaction which occurs before hadronization, $\Gamma(t \to W^+q) \approx 1.5$ GeV $> \Lambda_{QCD} \sim 200$ MeV.

2·1. *Top charged current decays in BSM*. – Alternative top quark CC decays are possible via charged technicolor particles, *e.g.* $t \to \pi_T^+ b$, and charged Higgs in Supersymmetry (SUSY) or with an extended Higgs sector $t \to H^+b$. The former decay channel has not been explored yet by CMS. The latter decay channel could be the leading channel for charged Higgs production. CMS has explored the discovery potential of this decay in the context of the minimal supersymetric model (MSSM). A more detailed description of this analysis can be found in the ref. [5]. The branching ratio of top to a charged Higgs boson depends on both its mass and $\tan\beta$ as shown in fig. 1(a). For $\tan\beta = 20$, the charged Higgs boson mostly decays to $\tau\nu$ for $m_{H^\pm} < m_t$ where m_t is the top mass [see fig. 1(b)]. For $m_{H^\pm} > m_t$, the two main decay modes are to tb or $\tau\nu$ as shown in fig. 1(b). Therefore, we can study the following main final states:

- If $m_{H^\pm} < m_t$, $t\bar{t} \to H^\pm W^\mp b\bar{b} \to (\tau^\pm \nu)(l^\mp \nu)b\bar{b}$.
- If $m_{H^\pm} > m_t$, $gg \to tbH^\pm \to (j_1 j_2)(bb(\tau^\pm \nu))$.
- If $m_{H^\pm} > m_t$, $gb \to tH^\pm \to ttb \to W^+W^-bbb \to j_1 j_2 \mu\nu bbb$ and $gg \to tH^\pm b \to ttbb \to W^+W^-bbbb \to j_1 j_2 \mu\nu bbbb$.

The final state $(\tau^\pm \nu)(l^\mp \nu)b\bar{b}$ was studied using fully simulated data, including pile-up, corresponding to a low luminosity of 2×10^{33} cm^{-2}s^{-1} [6]. The Level-1 (L1) trigger and High Level Trigger (HLT) selection includes a single muon, $p_T > 20$ GeV/c, and an electron, $p_T > 30$ GeV/c. The offline reconstruction uses jets with $E_T > 40$ GeV/c. The jet algorithm uses the iterative jet cone reconstruction with $\Delta R = 0.5$. Jets are required to be central $|\eta_{jet}| < 2.4$. At least three jets are required in the event and at least one of the jets tagged as a b-jet. The b-tagging algorithm is based on the impact parameter significance of tracks in the jet. The on-line tau reconstruction at L1 requires tau-like energy deposits in the calorimeters. Regional jet reconstruction around the L1 tau candidate is performed with $E_T > 20$ GeV/c. Electron fakes are reduced by requiring that the most energetic hadron calorimeter tower have $E_T > 2$ GeV. Then, the tau offline reconstruction follows using three concentric cones to identify tau candidates. Tau jet candidates are required to have $E_T > 40$ GeV. The total charge of the lepton plus the tau jet is required to be zero. To reduce background, the missing transverse energy (MET) has to be greater than 70 GeV. The main background channels are QCD $t\bar{t}$ with at least a single electron or muon tau jets, W+jets, and single top. The total systematic uncertainty is around 5%, where the main contributions come from b-tagging and tau identification. The 5σ discovery potential for a light $H^\pm$ boson at 30 fb^{-1} integrated luminosity including the effect of systematic uncertainties is shown in fig. 2.

The final state $(j_1 j_2)bb(\tau^\pm \nu)$ has also been studied in CMS [7]. Fully simulated data at low luminosity was used in this analysis. The main background channels are tau decays from QCD $t\bar{t}$, and taus from W decays. We can take advantage in this channel of the large MET for $H^\pm$ decays. The reconstruction of the top mass helps to suppress QCD multi-jet background. In addition, helicity correlations favoring H^+ decays over W decays due to the spin-parity properties of the decaying particles are employed. The main systematic uncertainties arise from tau identification, 8%, and the $t\bar{t}$ background, about 11%. For the other backgrounds, the MC statistics strongly dominate the measurement uncertainties and therefore the MC statistics uncertainties were used. Fig. 3 shows the 5σ-discovery region in the $m_A - \tan\beta$ plane.

The final states $j_1 j_2 \mu\nu bbb$ and $j_1 j_2 \mu\nu bbbb$ are the most interesting from the experimental point of view because an isolated muon is present which will satisfy the CMS trigger and the branching fraction into this decay is high [8]. The production of H^+ through heavy SUSY particles is not taken into account. The main background in these channels is $t\bar{t} + jets$. The selection includes a single muon trigger, $p_T > 20$ GeV/c, at least 5(6) jets with $E_T > 25$ GeV, and at least 3(4) b-tagged jets. The secondary vertex algorithm is used to identify b-jets. The best jet association is based on a likelihood ratio which contains information from the kinematic variables of jets, output of a kinematic fit on the $t\bar{t}$ system with a W and top mass constraint, and b-tagging discriminants. The largest systematic uncertainty is in the estimation of the large background. Even with a very optimistic analysis at an integrated luminosity of 30 fb^{-1} no visibility for these channels is obtained within the MSSM. The discovery contours for both final states are shown in fig. 4.

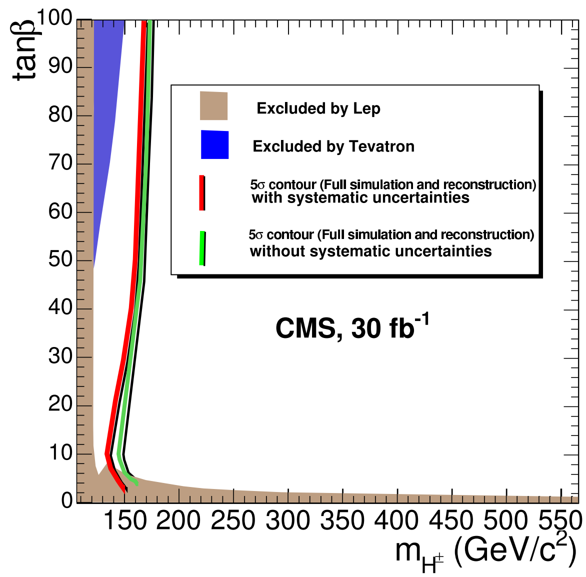

Fig. 2. – Discovery potential (5σ) for light charged Higgs boson with 30 fb^{-1} including the effect of systematic uncertainties.

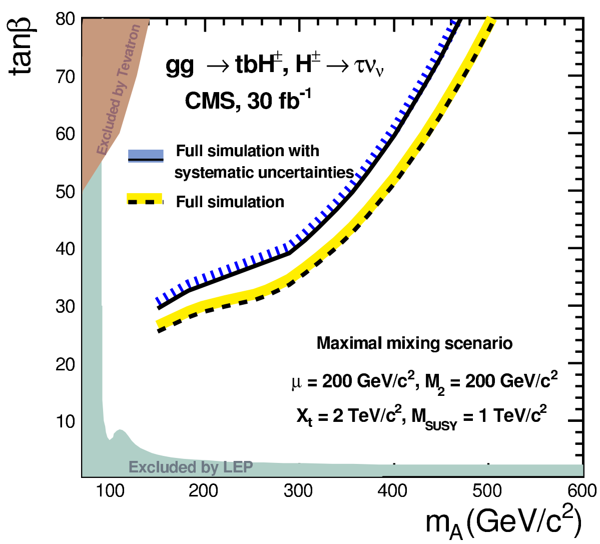

Fig. 3. – Discovery potential (5σ) for the channel $gg \to tbH^{\pm} \to (j_1 j_2)(bb(\tau^{\pm}\nu))$ at 30 fb^{-1} in the maximal mixing scenario with $\mu = 200$ GeV/c^2. The discovery regions with and without systematic uncertainties are shown. The regions excluded by LEP and Tevatron searches are also shown.

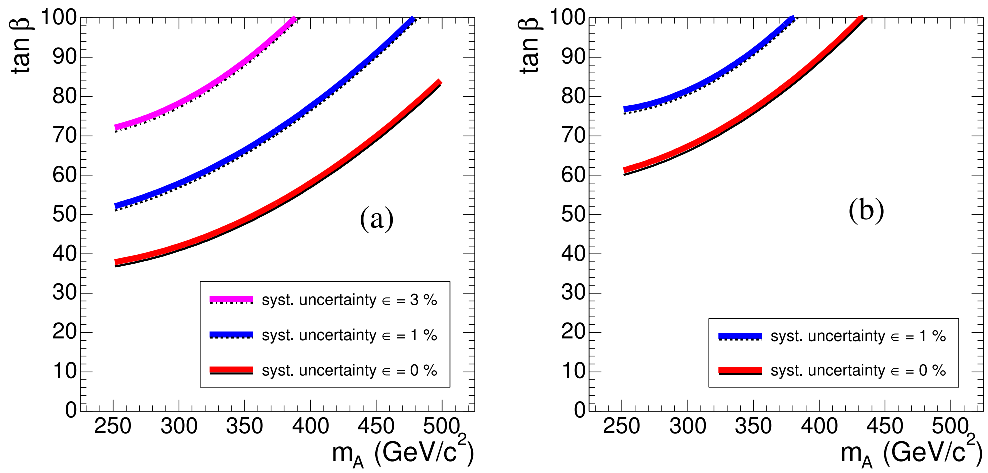

Fig. 4. – Discovery contours for $H^{\pm} \to tb$ decay for 30 fb^{-1} with a three b-jet final state (a)$j_1 j_2 \mu\nu bbb$, and a four b-jet final state (b)$j_1 j_2 \mu\nu bbbb$. The systematic uncertainty shown is due to estimated background leakage efficiencies of 0%, 1%, and 3%.

2˙2. *Top neutral current decays in BSM*. – Within SUSY, we can have new decay modes like $t \to \tilde{t}\tilde{\chi}^0$. These decays modes have not been explored in CMS. The decays explored are due to FCNC at loop level which are highly suppressed in the SM with branching fractions about 10^{-14}. Within the MSSM, we can have branching fractions of about 10^{-5}. The possible decays are $t \to \gamma + jet$, $t \to Z + jet$, and $t \to g + jet$. The last channel has not been studied because of the very high background. The analyses look for one SM top decay and another FCNC decay. Only the muon and electron decays from W and Z are studied. The main background sources are QCD $t\bar{t}$, single top (t-channel), ZW+jets, WW+jets, ZZ+jets, W+jets, Z+jets, Z$b\bar{b}$, and QCD. A detailed description of these analysis can be found in ref. [5].

3. – Top quarks in resonant production

In the SM at E_{cm} = 14 TeV, top quarks are produced via QCD production by the fusion of $q\bar{q}$ (10%) and gg (90%), via single top production, and via Higgs associated production $t\bar{t}H$. Beyond the SM, top quarks can also be produced in resonant production. In many models, there is a high potential to discover new physics in the top quark sector by searching for heavy resonances which decay into $t\bar{t}$ or $t\bar{b}$. Resonant states include Higgs bosons, new gauge bosons, Kaluza-Klein excitations of gluons and gravitons, technicolor-like dynamical states. New phenomena can be observed in the $m_{t\bar{t}}$ distribution as shape distortions or peaks. The distortions can be deviations of the distribution from the theoretical predictions due to enhancements or interferences of new physics [9]. Therefore, the $m_{t\bar{t}}$ distribution is a good observable and CMS will use it to carry on a model independent search. The $m_{t\bar{t}}$ distribution can be divided in three regions (see fig. 5). The low mass region, between 300 to 800 GeV/c^2, is where most of the SM background peaks and the standard tools to reconstruct top quark events can be applied. The medium region, between 800 to 1000 GeV/c^2, is where the standard tools begin to have low efficiency and a special reconstruction approach is needed to recover efficiency. The high mass region, above 1 TeV/c^2, is where the top quark is highly boosted. The decay products can be merged and the reconstruction of these objects requires a different approach. However, the event topology of these decays and the presence of high-p_T jets can help to reconstruct these special decays.

We are studying new techniques to improve the reconstruction of highly boosted top jets. The main problem with these events is that the decay products of the top jet are very close to each other. In fig. 6(a), the lego plot of the calorimeter towers of the four leading jets is shown from a sample of muonic QCD $t\bar{t}$. In fig. 6(a) is possible to easily distinguish two b-jets and two light jets from the W decay. In fig. 6(b), the lego plot is shown for the case of a narrow resonance $Z'(4\ TeV) \rightarrow t\bar{t}$. The top jet products are all merged into a high-p_T jet, and a second jet with lower p_T opposite to the leading jet. The most simple method to reconstruct these merged jets is to use a jet association based in ΔR. The leading jet is selected and the rest of jets around this jet are added vectorially to the leading jet. Then, the mass of this new merged jet (MJet) is obtained which has a mass near the top mass. An additional selection can be applied using topology variables, *e.g.* requiring that the merged jet be opposite to the second jet. The use of the variable ΔR is not suitable because of its strong dependency on the center of mass decay angle of the top. This produces distortions of the angular distributions and hence the possible spin determination of the parent resonance. A new variable called ψ has been studied to replace ΔR. The variable ψ is inspired by the k_T jet algorithm. Given a particle of mass M which has a two-body decay to particles of momentum p_1 and p_2 with angles θ_1 and θ_2 with respect to flight axis of M, we define $\psi = (p_1 + p_2)\sin((\theta_1 + \theta_2)/2)[min(p_1/p_2)]^{1/\alpha}/M$. The value of α is chosen to be 4 after an optimization using generated data. Using ψ instead of ΔR gives a slightly higher selection efficiency. Other variables [10] will also be studied in the future.

Another challenging reconstruction problem is the application of b-tagging to high-p_T jets. The b-tagging algorithms have been tested in high multiplicity events. It is observed that the algorithms are still functional in this extreme cases. However the non b-jet efficiency is very high. The cause of the increase in the mistagging rate is due to the increase of fake tracks being reconstructed. High-p_T jets have many tracks which are very close to each other producing overlapped hits in the pixel and tracker detector. There are currently efforts in train to reduce the track fake rate and improve b-tagging for these scenarios in CMS.

4. – Conclusions

The LHC will open a very rich top-quark sector to look for new physics beyond the SM. CMS has explored the discovery potential of BSM top quark decays like charged Higgs bosons and FCNC decays. Analyses of several final state decays of H^+ have been summarized in this note. These analyses are expected to be studied once the detector and the SM backgrounds are well understood. The sensitivity contours for a sample of 30 fb^{-1} were presented. In the case of FCNC decays, the expected sensitivity reach with 10 fb^{-1} extends two order of magnitude larger than the Tevatron. The search for heavy resonances decaying to top pairs is also being explored in CMS. The top pair invariant mass is a good observable to carry on a model independent shape search. CMS is studying different reconstruction techniques to improve the efficiency of selecting boosted top jets.

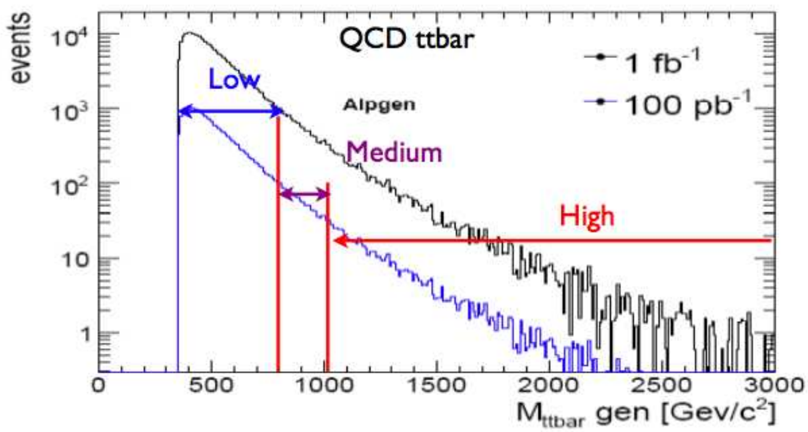

Fig. 5. – Distribution of $m_{t\bar{t}}$ from generated QCD $t\bar{t}$ events using Alpgen for 1 fb^{-1} and 100 pb^{-1}.

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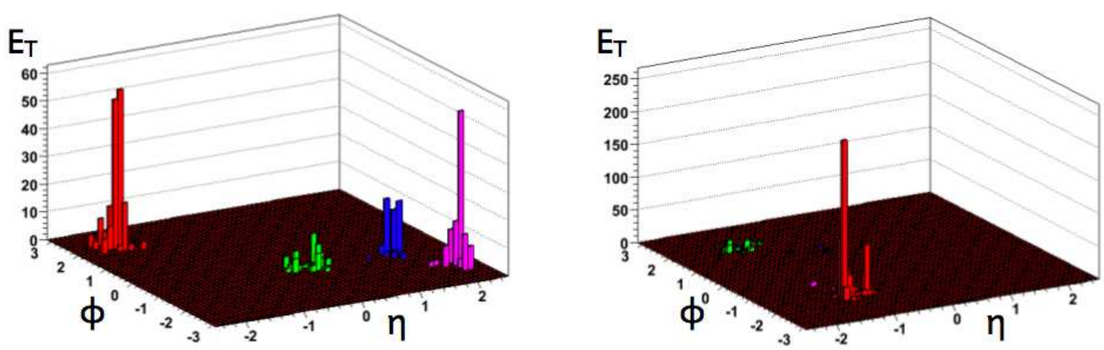

Fig. 6. – Lego plot of the four leading calorimeter of an event from (a) QCD $t\bar{t}$ sample and (b) $Z'(4\ TeV) \to t\bar{t}$ sample.