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Beyond Standard Model Searches with Top Quarks at ATLAS

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Summary. — At the LHC, the top quark is expected to provide a huge and clean signal. With about eight millions of expected top pairs and three millions of single top events produced per year in the low luminosity runs, and with a low level of backgrounds, the LHC will open a new opportunity for precision measurements of the top quark properties and for exotic topology searches involving top quarks.
As the ATLAS discovery potential on new physics with top quarks is being assessed with many analyses, this article focuses on two particular topics: heavy neutral resonances and charged Higgs boson searches with top quarks. The analyses and the ATLAS expectations are described.

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1. – Introduction

The LHC is expected to open a new era in new physics searches. The top quark sector is going to play an important role in this quest at three different levels. First, the top quark may couple to new particles in many extensions of the Standard Model (SM): additional bosons (Z', g^*, $H^\pm$, $\tilde{t}$, ...), heavy resonances (techni-η, π_t), 4^{th} quark generation, ... Top quark properties could be affected, giving clues for something unexpected at the top production or decay levels. Second, with more than one top event produced every second at LHC during low luminosity runs, data analyses can take advantage of the high integrated top quark statistics. Not only precise measurements, dominated by systematics, would be possible but also exotic top topology searches. Third, the specific signature of top events, mainly in leptonic channels, and the comparably low background production cross-sections lead to a high purity top sample after selection. As a consequence, the top quark will be a huge and clean signal at the LHC, which will allow stringent tests on top quark production and decay mechanisms.

The ATLAS collaboration is very active on beyond SM searches with top quarks. Many analyses have been developed to hunt down signs of new physics. They can be grouped into five different topics: (i) rare top decays and FCNCs in the top sector, (ii) 4^{th} quark generation sensitivity with top, (iii) SUSY particles ($\tilde{g}$, $\tilde{\chi}^0$, $\tilde{\chi}^\pm$, ...) searches with top, (iv) heavy neutral bosons decaying to top quark pairs, and (v) charged Higgs

bosons in two Higgs doublet models.
The first three topics are not discussed here because they are extensively described in this volume, respectively, in F. Veloso's, B. Holdom's and M. Milosavljevic's contributions: "top properties: prospects at ATLAS", "t prime searches at LHC" and "gluino in stop top at LHC". In this article, the first section describes the ATLAS analyses on high mass neutral resonances that couple to top quarks. The second section details the sensitivity potential of the ATLAS detector to charged Higgs bosons that appears in two Higgs doublet models.

2. – High mass neutral gauge boson searches in top pair events

Neutral gauge bosons can appear in extensions of SM, like in Grand Unified Theories. The gauge group symmetry breaking at the low-energy scale creates additional gauge bosons. If the Z'-like resonance is heavy enough, it can decay in a $t\bar{t}$ pair, which may interfere with the SM $t\bar{t}$ production. This can induce some modifications of the $t\bar{t}$ production cross-section, deformations in kinematics or $m_{t\bar{t}}$ spectra. This section describes two searches of heavy Z'-like resonances via top quark identification: generic narrow Z' searches in $m_{t\bar{t}}$ spectra, and high-p_T top quark searches [1]. The other analyses on heavy gauge boson searches with top quarks at ATLAS concern the Kaluza-Klein excitations of the gluon [2], little Higgs theories [3] or technicolor [4].

2˙1. *Generic narrow Z' searches.* – The goal is to assess the discovery potential of the ATLAS detector for a generic Z' boson in a model indepent way. Due to a large variety of models, the production cross-section, couplings with top, and mass of the Z' are free parameters in this analysis. However, its intrinsic width is required to be small compared to its reconstructed width. This allows searches in a fixed $m_{t\bar{t}}$ range. In addition, the gluon/Z'-like boson interference effects are not taken into account in this model independent analysis.
Top quark pair events in the "lepton+jets" (electron or muon) channels are selected to obtain a high purity and high statistics sample. The selection consists in two steps. The first one aims to reproduce trigger cuts, and reduce the level of instrumental and physical backgrounds: multijets, W+jets, Z+jets, dibosons and single-top production. The events satisfying a high-p_T isolated lepton trigger and standard off-line selection cuts are kept: exactly one isolated lepton ($p_T^l > 20$ GeV, $|\eta^l| < 2.5$), high missing transverse energy ($\not{E}_T > 20$ GeV), at least four jets ($p_T^{jet} > 20$ GeV, $|\eta^{jet}| < 2.5$) on which exactly two b-tagged jets. The purpose of the second selection step is to reconstruct the kinematics of the event, in order to discriminate the signal and the remaining backgrounds. The hadronic W boson coming from the top quark is reconstructed from the two light (non b-tagged) jets which are closest in the $\eta \times \phi$ space (smallest ΔR). Then the "hadronic top quark" is reconstructed combining the nearest b-tagged jet to the hadronic W. Two leptonic W boson candidates are formed because of the two-fold ambiguity in the reconstructed longitudinal neutrino momentum. The one providing the leptonic top mass closest to the mean value of the hadronic top mass is chosen. The level of SM backgrounds is then reduced by applying cuts on the reconstructed hadronic W and both top masses. The level of instrumental and physical SM backgrounds is assessed to be small, with $\sharp$(SM $t\bar{t}$)/$\sharp$(SM background) ≈ 70. However, the combinatorial background ($t\bar{t}$ events with a wrong b-jet, light jet or p_z^{ν} assignment) is important, leading to purity of well-reconstructed top quark pairs of 78%. Fig. 1 shows the reconstructed $t\bar{t}$ mass spectrum, used for the discovery potential determination, for the SM and from a heavy

Z' boson decay. In the SM case, the $\mathrm{t\bar{t}}$ production threshold around 350 GeV and the high mass tail are visible. For the $Z' \to t\bar{t}$ production, the shape is different, showing a Gaussian peak around the generated Z' mass.

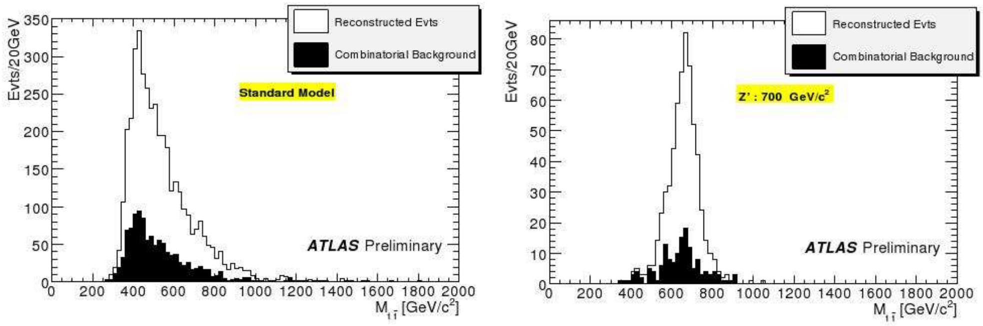

Fig. 1. – *Reconstructed* $\mathrm{t\bar{t}}$ *invariant mass spectra for Standard Model production (left) and for a 700 GeV* $\mathrm{Z}' \to \mathrm{t\bar{t}}$ *process (right). The instrumental and physical backgrounds are negligible.*

The discovery potential is determined from the $\mathrm{t\bar{t}}$ differential cross-section versus $\mathrm{m_{t\bar{t}}}$. The counting method is used with a sliding window technique to detect any excess of event in a mass window. The window width is fixed to twice the detector resolution for a given resonance mass, which varies from 40 GeV to 60 GeV for a Z' mass of 700 and 1400 GeV respectively. Thus, this method can only be applied to narrow resonance searches, whith $\Gamma_{\mathrm{Z}'} \ll 50$ GeV. Fig. 2 shows the discovery potential of a generic narrow $\mathrm{t\bar{t}}$ resonance for different integrated luminosity scenarii, and the $\mathrm{t\bar{t}}$ selection efficiency. For example, the resulting sensitivity shows that a 700 GeV Z' resonance produced with a cross-section of $\sigma(\mathrm{pp} \to \mathrm{Z}') \cdot \mathrm{BR}(\mathrm{Z}' \to \mathrm{t\bar{t}}) > 11$ pb should produce an excess of selected events $S/\sqrt{B}$ greater than 5 σ (statistics and systematics combined) with 1 fb^{-1} of data.

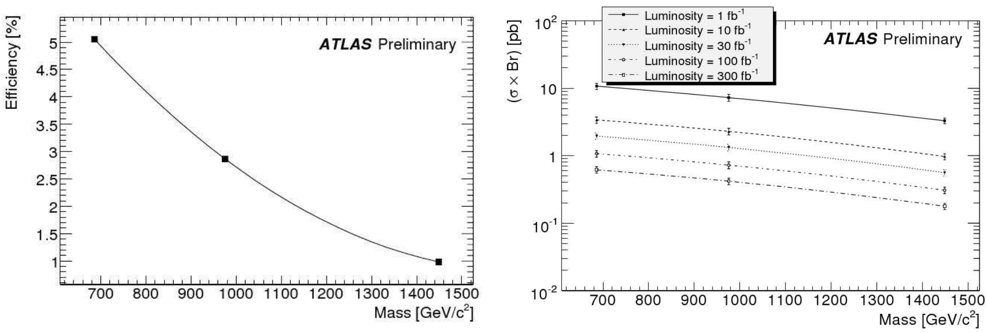

Fig. 2. – $\mathrm{Z}' \to \mathrm{t\bar{t}}$ *selection efficiency versus* Z' *mass (left), and discovery potential of a generic narrow* $\mathrm{t\bar{t}}$ *resonance for different integrated luminosity scenarii (right).*

The systematic errors come from theoretical and experimental uncertainties. The main effect arises from the uncertainties on the reconstruction efficiency of signal and background (17%). This affects the 5 σ Z' cross-section limit at the level of 8.3%. The uncertainties of $^{+6.2}_{-4.7}\%$ on background production cross-sections (SM $\mathrm{t\bar{t}}$ included) change the cross-section limits by 3.1%. The width of the window for the counting method is varied by $\pm$ 1σ, leading to an effect of 2 to 11% on the discovery potential. The uncertainty on luminosity ($\pm$5%) is translated to a 2.5% effect on the 5 σ Z' cross-section limits. The uncertainty on jet energy calibration is negligible since the jets are recalibrated with the hadronic W boson.

In this analysis, the ATLAS discovery potential for a model-independent $Z' \to t\bar{t}$ is assessed. One limitation of this method comes from the explicit selection of the three decay products of the hadronic top. Indeed, the drop of efficiency observed as a function of the $t\bar{t}$ mass on fig. 2 can be explained by the fact that the produced particles are closer together when the Z' mass is higher. This issue can be recovered by other techniques or other jet finding algorithms, which are better at resolving nearby jets. This is described in the following part.

2˙2. *High-p_T top quark searches.* – At the LHC, massive objects like top quarks, W and Z bosons could be produced with a very large transverse momenta. In many cases, these objects decay hadronically, producing a set of collimated jets. Then, the jet reconstruction algorithms with large cone sizes ($\Delta R > 0.5$) show a loss of efficiency, as shown in the previous part on fig. 2, especially when the ΔR distance between jets is smaller than twice the jet cone radius. This often occurs for boosted hadronic top quarks, with momenta larger than 500 GeV, where the quarks are so close than they can be reconstructed as a single jet. New techniques and tools are being developed to solve this new experimental issue. In this part, a new method is described to reconstruct boosted hadronic top quarks.

In order to reconstruct large single jets with underlying substructures, the idea is to use the k_T clustering jet algorithm. It fulfils the theoretical requirements on jet algorithms, and tends to reconstruct the substructures in a jet, due to fragmentation and radiation effects. Thus, k_T jets are adapted to reconstruct boosted hadronic top quarks.

The discrimination of signal hadronic top quarks and jets originating from a single hard parton requires an advanced selection procedure. Firstly, high-p_T k_T jets are considered ($p_T^{jet} > 300$ GeV). Secondly, a multivariate sequential selection is used, with several discriminant variables: the mass of the jet and the energy scale values at which the monojet splits into two, three and four jets. The mass of a k_T jet is defined as the invariant mass of all the jet's constituents, which are the calorimeter cells. However, jet constituents are not calibrated. It is necessary to develop a cell-level calibration method, then to apply the calibration and rebuild the jet. Fig. 3 shows the jet mass distributions for the hadronic top signal and for the multijet background, after the jet recalibration. For the signal, a peak corresponding to monojet top quarks is visible around $m_{top} \approx 190$ GeV. For jets originated by light quarks and gluons, the mass spectrum drops exponentially. Fig. 4 shows the selection efficiency for the signal and the background. The selection efficiency now increases with p_T^{top}. It is important to point out that the selection cuts have not been optimized for a particular region in phase space, but to achieve a maximal efficiency for top monojets while keeping the light jet efficiency below 10%.
The systematic uncertainties on the top monojet selection performance come from the modelling and the reconstruction of the jets. Indeed, the hadronization model affects many jet variables. The ensuing systematic uncertainty is assessed to at most a few percents. The uncertainty can also come from noise and low-energy calorimeter cells in the outer edge of a jet. They can make a significant contribution to the mass of the jet. The performance of the k_T algorithm, the jet energy resolution and scale will also potentially lead to large systematic uncertainties since the distributions for light jets are exponential. Thus, for this analysis, it is very important to check calibration and selection performance with real data.

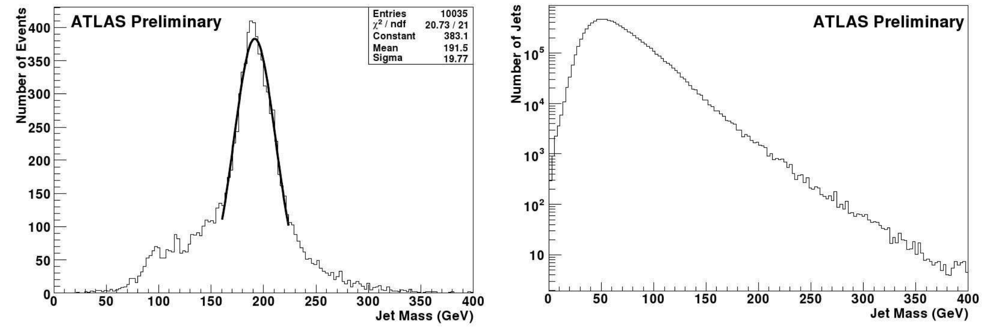

Fig. 3. – *Invariant jet mass distributions for reconstructed jets in* $Z' \rightarrow t\bar{t}$ *(left) and multijet (right) events.*

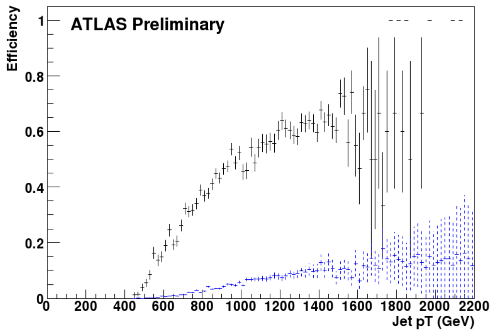

Fig. 4. – *Selection efficiency for jets coming from the hadronic top quark (solid) and coming from hard light partons (dashed).*

This analysis takes place in the context of high mass $t\bar{t}$ resonance searches, that produce boosted top quarks, and thus can no longer be reconstructed by a fixed-cone jet algorithm with a high efficiency. The goal of this analysis was to provide an estimate of the discriminating power between top monojets and light jets. A specific physics analysis is needed to optimize the cuts for the relevant region, like requirements on the lepton from the semileptonic decay of the other top quark in $Z' \rightarrow t\bar{t}$ events for example. A multivariate tool could also lead to further improvement in the selection performance.

3. – Charged Higgs boson searches

Several extensions to the SM Higgs sector predict charged Higgs bosons. In this section, only charged Higgs bosons that appear in 2 Higgs doublet models (2HDM) are considered, and in particular the type II-2HDM model, which is the Higgs sector of the MSSM. In this model, $H^{\pm}$ bosons are strongly coupled to the top quark. Thus precise measurements of the top quark properties or exotic top topology searches are a good method to discover charged Higgs bosons.

Different strategies involving top quark have been developed for $H^{\pm}$ sensitivity. They depend on the two additional free parameters in the 2HDM: the mass of the charged Higgs boson and the ratio of the vacuum expectation value of the two Higgs doublets ($\tan\beta$). As $H^{\pm}$ are involved in top quark production, the channels of interest are the $t\bar{t}$ production and the three single top production mechanisms. This section describes the direct searches for charged Higgs bosons in $t\bar{t}$ and single top channels. Precise measurements of top quark pair or s-channel single top production cross-sections [5][6] also show an interesting discovery potential.

3.1. *Light charged Higgs boson searches.* – If the charged Higgs boson is lighter than the top quark, the decay channel $\mathrm{t} \to \mathrm{H}^{\pm}\mathrm{b}$ is kinematically allowed. The charged Higgs boson can be produced in the $\mathrm{t\bar{t}}$ decay channels. Three channels were investigated, with $H^{\pm}$ decaying to τ lepton: the "hadronic tau+jets", the "leptonic tau+jets" and the "hadronic tau+lepton" $\mathrm{t\bar{t}}$ final states. The $\mathrm{t\bar{t}}$ production cross-section in these channels is high for large $\tan\beta$. For the three analyses, the events are triggered by a high-p_T isolated lepton (including hadronic τ) plus high missing transverse energy. Additional high-p_T jets can also be required at the trigger level. The main backgrounds in the three channels are the multijet processes, where a jet can fake an isolated lepton (including isolated hadronic τ), the $\mathrm{W}(\to \tau\nu) + \text{jets}$ and SM $\mathrm{t\bar{t}}$ processes.

The $\mathbf{t\bar{t}} \to (\mathbf{bH^{\pm}})$ $(\mathbf{bW^{\pm}}) \to (\mathbf{b}\tau^{\pm}_{\mathbf{had}}\nu)$ $(\mathbf{bjj})$ channel is challenging because no isolated lepton is present in the event. The following set of cuts is used to preselect the signal and suppress the backgrounds: exactly one τ-tagged jet ($\mathrm{p_T^{\tau}} > 25$ GeV) with a veto on any other isolated lepton, high missing transverse energy ($\not{E}_\mathrm{T} > 30$ GeV), exactly two b-tagged jets coming from the two top quarks ($\mathrm{p_T^{b-jet}} > 15$ GeV) and at least two additional jets ($\mathrm{p_T^{jet}} > 15$ GeV). Further background rejection is possible with a full reconstruction of the W boson and the hadronic top quark in the event. The procedure is similar to the one described in sect. **2**.1. Since the $H^{\pm}$ cannot be fully reconstructed, the transverse momentum and azimuthal angle distributions are used to select the top quark decaying to $H^{\pm}$. In order to remove SM $\mathrm{t\bar{t}}$ background events, a likelihood discriminant is developed to exploit the differences between the 2HDM $\mathrm{t\bar{t}}$ and SM $\mathrm{t\bar{t}}$ events. It is based on the reconstructed $H^{\pm}$ mass and on the polarization of the τ lepton.

The $\mathbf{t\bar{t}} \to (\mathbf{bH^{\pm}})$ $(\mathbf{bW^{\pm}}) \to (\mathbf{b}\tau^{\pm}_{\mathbf{lep}}\nu)$ $(\mathbf{bjj})$ channel is characterized by a single isolated lepton and three neutrinos in the final state. A full reconstruction of the event is therefore impossible. The event selection is based on exactly one isolated electron or muon ($\mathrm{p_T^{l}} > 5$ GeV), high missing transverse energy ($\not{E}_\mathrm{T} > 120$ GeV), at least four high-p_T central jets ($\mathrm{p_T^{jet}} > 40$ GeV, $|\eta^{\mathrm{jet}}| < 2.5$), of which exactly two are b-tagged. The reconstruction and identification of the hadronic W and top are also required. For this, the two b-jets are assigned to the hadronic and leptonic top quarks using the angular and charge correlations between the b-tagged jets, the lepton and the hadronic W. Finally, the remaining background, SM $\mathrm{t\bar{t}} \to \mathrm{l} + \text{jets}$ events, is reduced exploiting the difference in the leptonic $W^{\pm}$ or $H^{\pm}$ decay angle and transverse mass.

The $\mathbf{t\bar{t}} \to (\mathbf{bH^{\pm}})$ $(\mathbf{bW^{\pm}}) \to (\mathbf{b}\tau^{\pm}_{\mathbf{had}}\nu)$ $(\mathbf{bl^{\pm}}\nu)$ channel is expected to have a low background contamination because of the high-p_T isolated lepton, the hadronic τ lepton and the three neutrinos. The main backgrounds are SM $\mathrm{t\bar{t}}$ events in the τ+lepton channel. The selection requires at least one isolated central and high-p_T lepton ($\mathrm{p_T^{l}} > 10$ GeV), at least one τ-tagged jet ($\mathrm{p_T^{\tau}} > 40$ GeV), the hadronic τ and the lepton must have opposite charge, high missing transverse energy ($\not{E}_\mathrm{T} > 175$ GeV), at least three high-p_T jets ($\mathrm{p_T^{jet}} > 20$ GeV), on which at least one is b-tagged.

3.2. *Charged Higgs bosons in single top quark production.* – If the charged Higgs boson is heavier than the top quark, then it decays mainly via $\mathrm{H}^{\pm} \to \tau^{\pm}\nu$ or tb. In this latter case, its production can interfere with single top production $\mathrm{bg} \to \mathrm{b}^* \to (\mathrm{tW}^{\pm})/(\mathrm{tH}^{\pm})$. In this analysis, another mechanism, $\mathrm{gg} \to \mathrm{tbH}^{\pm}$ for which one initial gluon splits into a $\mathrm{b\bar{b}}$ pair, has been taken into account and correctly merged to the first one. Two channels were investigated, with a heavy charged Higgs boson decaying to tb or to $\tau\nu$. The trigger conditions and the main backgrounds are the same as in $H^{\pm}$ searches in $\mathrm{t\bar{t}}$ events.

The gb → tH$^{\pm}$ → (bjj) ($\tau^{\pm}\nu$) channel has no isolated lepton, so special attention is given to reduce the multijet backgrounds. The preselection requires exactly one high-p_T high quality hadronic τ lepton ($\mathrm{p_T^{\tau}} > 50$ GeV) with a veto on any other isolated lepton ($\mathrm{p_T^{l}} > 7$ GeV) to suppress the dileptonic $\mathrm{t\bar{t}}$ background, high missing transverse energy ($\not{E}_T > 40$ GeV), at least three high-p_T jets ($\mathrm{p_T^{jet}} >$ 15 GeV), of which exactly one is b-tagged. For further discrimination of all backgrounds without hadronically decaying top quarks, a reconstructed W or top is required. The selection is based on a χ^2 estimator with the masses of the W and the top quark. Finally, the remaining SM $\mathrm{t\bar{t}}$ background is reduced using a multivariate likelihood based on angular and kinematic discriminant variables.

The gb → tH$^{\pm}$ → (bjj) (tb) → (bjj) (bl$^{\pm}\nu$ b) channel is particularly challenging because the final state includes one high p_T lepton, one neutrino, two light jets and at least three b-jets. This signature is similar to $\mathrm{t\bar{t}}$+b-jets events in the "lepton+jets" channel and efforts were concentrated to reduce this background. The events are required to have exactly one high-p_T central isolated electron or muon ($\mathrm{p_T^{l}} \gtrsim 20$ GeV, $|\eta^{l}| < 2.5$), at least five high-p_T jets ($\mathrm{p_T^{jet}} >$ 20 GeV $|\eta^{\mathrm{jet}}| < 5$) of which at least three are b-tagged. Then the two W bosons and the two top quarks are explicitly reconstructed. Due to the large number of jets in the event, a first likelihood function is built to reduce the combinatorial background. The final selection, which aims at reducing the $\mathrm{t\bar{t}b\bar{b}}$ background, is made on a second multivariate likelihood discriminant.

3˙3. *ATLAS sensitivity for a charged Higgs boson.* – Systematic uncertainties affect the sensitivity of the analyses. In all channels, the signal is observed as an excess of events over the main background of SM $\mathrm{t\bar{t}}$ production. Uncertainties on signal or background stem from two sources. From the theoretical side, the production cross-section for $\mathrm{t\bar{t}}$ events is known with a 12% error. In addition, an uncertainty around 5% is associated to the branching ratios of the $\mathrm{H^{\pm}} \to$ top, τ or light jets. From the experimental side, the uncertainties on the performance of the tagging algorithm (b- or τ-tagging) and the calibration of light, τ and b-jets are translated into uncertainties on the sensitivity of the analyses. The uncertainty from the luminosity measurement is also taken into account. In order to reduce the systematic uncertainty coming from the estimation of the background level, a data-driven technique has been developed. The idea is to use $\mathrm{t\bar{t}} \to \mu + \mathrm{X}$ events in real data, and to replace the muon by a τ to get the normalization and the shape of the main background $\mathrm{t\bar{t}} \to \tau + \mathrm{X}$.

The five channels are combined to give the total charged Higgs boson sensivity. The ATLAS discovery potential is shown fig. 5. With 10 fb^{-1} of data, if the $H^{\pm}$ boson is light ($m_{H^{\pm}} < m_{top}$), it could be discovered for small or high values of $\tan\beta$. Nevertheless, the intermediate region $5 < \tan\beta < 15$ needs more statistics to be covered, because the $\mathrm{t\bar{t}} \to \mathrm{H^{\pm}X}$ cross-section has a minimum. If the $H^{\pm}$ boson is heavy, a discovery is possible for high values of $\tan\beta$. A model-independent search is also performed in terms of sensitivity on the branching ratio $\mathrm{t} \to \mathrm{H^{\pm}b}$ as a function of $m_{H^{\pm}}$, assuming $\mathrm{BR(H^{\pm}} \to \tau\nu) = 1$. The results, presented in fig. 5, show that it would be possible to discover the charged Higgs boson if the branching ratio $\mathrm{t} \to \mathrm{H^{\pm}b}$ is larger than about 1-3%. The model-independent sensitivity for a heavy $H^{\pm}$ is assessed to $\sigma(\mathrm{pp} \to \mathrm{tH^{\pm}} \to$

$t\tau^{\pm}\nu) > 20$ pb for $m_{H^{\pm}} \approx 600$ GeV and 30 $fb^{-1}$of data.

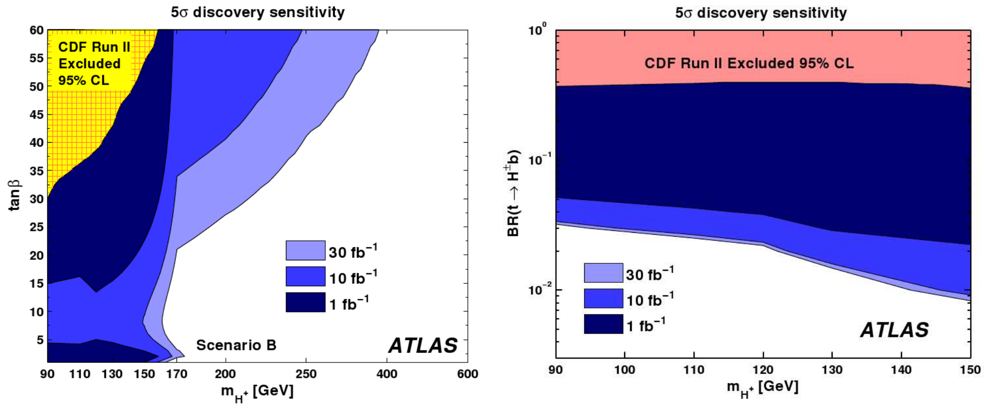

Fig. 5. – *Left: Discovery contours* ($m_h - \max$ *scenario) for a charged Higgs boson in top events, as a function of* $\tan\beta$ *and* $m_{H^{\pm}}$. *Statistical and systematic uncertainties are included, except the one arising from simulation statistics. Right: Discovery contours for model-independent light* $H^{\pm}$ *searches in the* $(BR(t \to H^{\pm}b),\ m_{H^{\pm}})$ *plane.* $BR(H^{\pm} \to \tau\nu) = 1$ *is assumed.*

4. – Summary

Thanks to the high top statistics and the low level of background, the top quark will be a good tool to search for physics beyond SM. The discovery potential of the top quark is widely covered at ATLAS, via direct searches and precision measurements. These analyses show that new physics sensitivity at the TeV scale could be possible with a few fb^{-1}, but some complex topologies or rare signals could require hundreds of fb^{-1}. In all analyses, the use of data will help to understand the detector and reconstruction effects, and to control the level of background.

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