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Beyond the Standard Model searches with the top quark at the Large Hadron Collider

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Top quark events resulting from proton-proton collisions at high energies in the new Large Hadron Collider will be collected by the ATLAS and CMS experiments and have the potential to probe New Physics beyond the Standard Model. The study of the production and decay of the Top quarks might reveal high-mass resonances, extra-dimensions, new flavor dynamics, and evidence for a 4^{th} generation, among other possibilities. Specific experimental techniques for event reconstruction and for the control of the background are required to increase the reach for New Physics. An overview of some of these techniques is given along with the expected sensitivity of the ATLAS and CMS experiments for some scenarios.

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1. Introduction: Experimental challenges

The Large Hadron Collider (LHC) at CERN will collide two counter-rotating proton beams at a center of mass energy of 14 TeV. Both ATLAS and CMS are general purpose experiments ready to acquire the events produced at the LHC [1]. The main experimental challenges are to retain a high trigger efficiency, to mantain a fast readout with the full detector granularity in the short time ($\sim$25 ns) between collisions, and to achieve a good synchronization between the detectors and the accelerator.

Re-discovering to the Top quark at the LHC is one of the priorities at startup. The Top quark is the only known fermion with a mass close to the energy scale at which the Electroweak Symmetry is broken ($M_t \approx 2.14 M_W$) and it completes the 3^{rd} quark family in the context of the Standard Model (SM). The measurements of the Top quark properties have been gaining extraordinary precision since its discovery in 1995 at the Tevatron [2]. Several examples were reported in this Conference and are summarized in [3]. At the LHC, Top quarks will be mainly produced in pairs ($t\bar{t}$) by gluon-gluon fusion with a cross section $\sigma \sim$908 (414) pb at $\sqrt{s}$=14 (10) TeV center of mass collisions [4]. Top quark production is expected to be mainly contaminated by QCD and W/Z events.

The ATLAS and CMS experiments will use the first Top quark events to understand the detectors and re-establish the measurements at the LHC. Top quark events have a fairly clear experimental signature with two b jets and the decay products of two W bosons, in which the decay products are kinematically correlated and the sum of their 4-momenta can be constrained to M_t and M_W. The experimental measurement of the missing transverse energy ($\not{E}_T$) due to the neutrinos produced in the event may also help to further constrain the kinematics of the event. Jet energy and $\not{E}_T$ scales can therefore be commissioned using Top quark events with early data assuming M_t and M_W from the Tevatron and LEP measurements. Moreover, the correct assignment of the two b jets can provide a direct measurement of the b-tagging efficiency, i.e. the efficiency of the algorithms used to identify b jets [5, 6].

The "re-discovery" of the Top quark at the LHC will also be a crucial step in the study of the main backgrounds for more rare processes, such as Higgs boson production or Supersymmetry (SUSY) signatures. New production mechanisms such as high-mass resonances like leptophobic Z', Kaluza-Klein gluons or even a 4^{th} quark generation might also generate $t\bar{t}$ pairs if they are produced at the LHC. Therefore, the search for deviations of $t\bar{t}$ production parameters with respect to the SM predictions might reveal New Physics and hopefully shed some light on what is the Top quark role in the mechanism that breaks the Electroweak symmetry. New Physics can also be searched in the decays of the Top quarks. The measurement of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements involving Top quarks (i.e. V_{tq}), the measurement of the branching ratios of rare processes generated by Flavor Changing Neutral Currents, or the coupling to a charged Higgs in the SUSY context are some examples. The study of anomalous couplings in the Wtb vertex and consequent deviations in the Top quark polarization with respect to the SM predictions are also of great interest. A focus on New Physics searches in the Top quark sector which can be performed almost directly with early data collected by the ATLAS and CMS experiments is briefly discussed in the next Section.

2. On the road to discovery

2.1 Resonances in the $t\bar{t}$ invariant mass spectrum

Both the ATLAS and CMS experiments intend to use the lepton+jets sample to probe heavy resonances production in the $t\bar{t}$ invariant mass spectrum ($M_{t\bar{t}}$) in the first data-taking period. The latest results from the CDF (D0) experiment at the Tevatron set the limits for heavy resonances production in the $M_{t\bar{t}}$ spectrum at $M(Z') >$805 (820) GeV/c^2 with 2.8 (3.6) fb^{-1} of data [7].

The μ+jets sample provides a large statistics sample and can be selected using a non-isolated muon trigger, which provides a non-biased sample over a large range of the $M_{t\bar{t}}$ spectrum. The threshold values used for event selection are not quoted in this manuscript as they depend on the detector and can be found in [8, 9, 10]. The common event selection requires one muon, no other isolated leptons found in the detector, and at least 4 jets. In the low energy region of the $M_{t\bar{t}}$ spectrum the muon should appear isolated in the event. However, for large $M_{t\bar{t}}$ reconstructed values, the decay products of each Top quark will have a large boost and will be collimated, and the muon appears no longer isolated but it will acquire a large transverse momentum relatively to the nearby jet(s) (p_T^{rel}). Isolated or high-p_T^{rel} muons may thus constitute an experimental signature of boosted $t\bar{t}$ events (and a similar behavior is expected for electrons in the e+jets channel [8]). Both ATLAS and CMS experiments plan to use a 2D-discriminator based on isolation and p_T^{rel} variables to select efficiently the signal and to reject the large QCD background, where the muons are expected to be found within jets with low p_T^{rel} values. The reconstruction of $M_{t\bar{t}}$ in the μ+jets sample also requires:

- to determine the momentum of the undetected neutrino making use of $\not{E}_T$ measurements together with the $W \rightarrow \mu\nu_\mu$ mass constraint;
- to correctly assign the jets to the $t\bar{t}$ decays (the jet multiplicity can be larger than what is expected from $t\bar{t}$ events due to pile-up, multiple-interactions and ISR/FSR radiation effects).

The CMS collaboration plans to select the events based on a χ^2 value, where the χ^2 term makes use of the reconstructed M_W and M_t values as well as of other variables, such as the angles between the muon and the candidate b jet in the event. This method yields tries to keep a minimum reliance on the Monte-Carlo (MC) simulation which is only used to describe the experimental resolutions and is robust over a large range of the $M_{t\bar{t}}$. A fit imposing the kinematical constraints of the jets, muon, and neutrinos is further performed improving both the choice for the best jet pairing and the $M_{t\bar{t}}$ energy resolution. The projected yields for signal and background events in a startup scenario with proton-proton collisions at 10 TeV are shown in Table 1.

Table 1: Expected event yields for semileptonic muon events as projected by the CMS collaboration for an integrated luminosity of 100 pb^{-1} at $\sqrt{s}$=10 TeV [9]. Only statistical uncertainties are shown.

	$t\bar{t} \rightarrow \mu$+jets	other $t\bar{t}$	QCD	W/Z+jets
Expected (100 pb^{-1} at 10 TeV)	6255	35×10^3	$> 12 \times 10^6$	4.470×10^6
After fit convergence	910 ± 2	147 ± 1	183 ± 20	375 ± 15

With increased confidence in the simulation, methods relying on MC probability distributions for the signal and background jet kinematics may also be used to identify the hadronic Top quark decay. The ATLAS collaboration plans to use such methods which are expected to have a very good discriminating power against the QCD and W/Z+jets backgrounds. By requiring one of the jets to have at least p_T>300 GeV/c, which is corresponding to the collimated jet from the hadronic Top decay products, a likelihood ratio variable can be constructed based on the jet mass and on the scales at which this broad jet can be decomposed into sub-structures [11]. Table 2 summarizes the event yields expected by ATLAS with this method for proton-proton collisions at 14 TeV.

Table 2: Expected event yield and sensitivity to a Z' resonance in the e+jets and μ+jets sample as projected by the ATLAS collaboration for an integrated luminosity of 1 fb^{-1} at 14 TeV [8]. Event yields after a cut on the likelihood ratio discriminator $y_L > 0.6$ are shown for signal and background, correspondingly. Only statistical uncertainties are shown. The last column represents the expected sensitivities for 95% CL limits on the signal production cross section multiplied by the branching ratio.

$M_{t\bar{t}}$	SM $t\bar{t}$	QCD	$Z' \to t\bar{t} \to$ l+jets	95% CL on $\sigma(Z') \times BR(Z' \to t\bar{t})$
2 TeV/c^2	21.9 ± 1.0	1.9 ± 0.5	9.4 ± 0.2 %	550 fb
3 TeV/c^2	2.9 ± 0.1	0.5 ± 0.2	13.6 ± 0.2 %	160 fb

The technique of reconstructing broad jets by studying the jet substructure is indeed powerful and can be used as a Top-jet tagging algorithm. The CMS Collaboration has developed such an algorithm which is expected to have a signal efficiency of ≈46% and a low fake rate (≈2%). This technique can also be applied to study the $t\bar{t}$ fully hadronic channel [12].

Using the techniques described above and profiting from the large statistics for $t\bar{t}$ production at the LHC, both ATLAS and CMS experiments expect to reach the current limits set by the Tevatron experiments with a few hundreds of pb^{-1} of data collected at $\sqrt{s}$=10 TeV. This is shown in Fig. 1 for the CMS experiment.

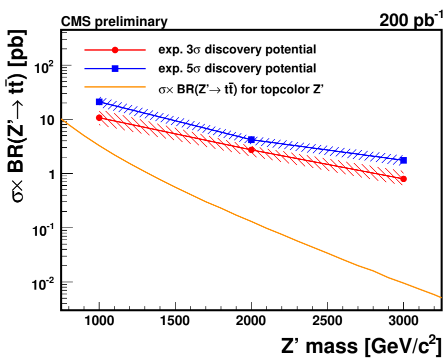

Figure 1: Expected limits on $\sigma(Z') \times BR(Z' \to t\bar{t})$ as a function of the Z' mass, for which an observation of $Z' \to t\bar{t}$ production is expected for 3σ and 5σ, respectively, for an integrated luminosity of 200 pb^{1} collected with the CMS detector at $\sqrt{s} = 10$ TeV. The cross section of the topcolor Z' is superimposed for reference.

2.2 Heavy flavor content of Top quark events

The study of the heavy flavor content of Top quark events can be used to look for non-SM events contamination. A simple counting experiment of the number of reconstructed b-jets can be used to measure the ratio $R = B(t \to Wb)/B(t \to Wq)$. The measured b-jet multiplicity can be compared with the expectations based on the b-tagging and mistaging efficiencies and on the fraction of $t \to Wb$ events correctly reconstructed and selected. This measurement is mainly affected by the uncertainty in the b-tagging efficiency and by the modeling of background events. After the commissioning the CMS experiment with cosmic muons, the alignment of the tracking detectors has already been determined; it is expected that the b-tagging efficiency will be known with an uncertainty of 10% after a total integrated luminosity of 100 pb^{-1} is acquired from collisions at 14 TeV. If Top quark events in both lepton+jet and dilepton final states are used to probe the heavy flavor content the experimental challenges mainly come from correctly assigning the jets to those from Top quark decays. The contamination from jets due to ISR/FSR and background processes can be estimated directly from data [13]. In the dilepton channel the lepton-jet invariant mass spectrum can be used as correct lepton-jet assignments are kinematically bounded by the $M_{lj} \leq \sqrt{M_t^2 + M_W^2}$. In the lepton+jets channel the previously discussed χ^2 technique can be used. The shape of the misassignment spectrum can be estimated directly from data by randomly rotating the momentum of the selected leptons or by pairing leptons with jets from different events. These simple techniques help to reduce substantially the uncertainty in the modeling of the background by removing reliance on the MC simulation. The total uncertainty in the measurement of R is expected to be systematic dominated after a total integrated luminosity of 250 pb^{-1} (1 fb^{-1}) at 10 TeV and is expected to be ∼9% (15%) in the dilepton (lepton+jets) channel. Figure 2 shows the result of a simultaneous measurement of R and the level of contamination by non-Top decay jets. The agreement with MC simulation is good and, in order to reduce the uncertainties, sensitivity to deviations from the SM predicted value ($R \approx 1$) will require more data.

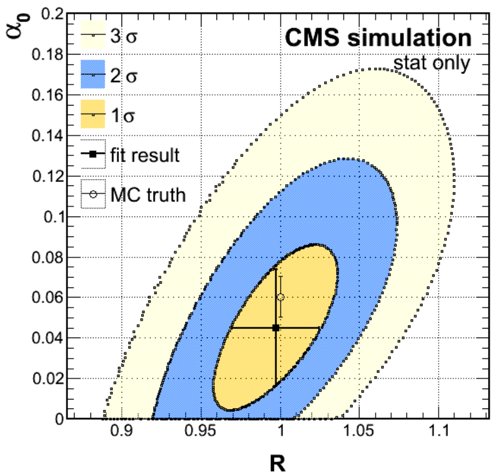

Figure 2: Contour plot for a simultaneous fit to R and the background level (α_0) in the dilepton sample. Only stat. uncertainties are shown.

3. Conclusions

With the upcoming startup of the LHC Top quark production will be re-discovered and provide calibration for the ATLAS and CMS. Both experiments expect to reach the current limits set by the Tevatron experiments for $M(Z')$ with a few hundreds of pb^{-1} of data collected at $\sqrt{s}$ =10 TeV. The heavy flavor content of $t\bar{t}$ events can also be probed and the ratio $R = B(t \to Wb)/B(t \to Wq)$ is expected to be measured with the same uncertainty as the current measurements at the Tevatron already with 250 pb^{-1} of data. Using early data from LHC collisions, the expected results from the ATLAS and CMS experiments can already reach the sensitivity of the Tevatron experiments.

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