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Perspectives for top quark physics at LHC

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Abstract

The Large Hadron Collider (LHC) will provide a huge amount of top-antitop events, making the LHC a top quark factory. Precision measurements in the top quark sector will allow for a detailed study of electroweak (and flavour) symmetry breaking mechanisms. All the properties of the top quark will be obtained, based on the measurement of its mass, cross section and decay branching fraction. The large top quark sample available from the start of LHC will also play an important role in commissioning the ATLAS and CMS detectors during the first data-taking period. A brief overview of the top quark measurements within the Standard Model is given, together with a review of possible new physics scenarios in production and decay mechanisms.

1 Introduction

In the Standard Model (SM) the top quark is a spin $1/2$ fermion with electric charge $Q_{em}^t = 3/4 |e|$, the weak isospin partner of the b quark, and a colour triplet [1, 2]. Even within the SM the top quark is a very special object because of its much larger mass with respect to all the other fermions and the top quark Yukawa coupling is surprisingly close to one. The top quark lifetime, $\tau_t \approx 0.4 \times 10^{-24}$ s, is much smaller than the typical time for the formation of QCD bound states, $\tau_{QCD} \approx 1/\Lambda_{QCD} \approx 3 \times 10^{-24}$ s. Therefore, the top quark decays long before it can hadronize [3], providing a very clean source for fundamental information.

Top quark pair production at the LHC happens mainly via gluon fusion. Final states result from the decay of two top quarks into Wb, with a branching fraction close to unity, and the subsequent decay of the W boson. The resulting channels are therefore called fully hadronic ($\approx 46\%$), semi-leptonic ($\approx 44\%$) and fully leptonic ($\approx 10\%$), depending on the type of W decay.

The Large Hadron Collider (LHC) will start to collide protons in 2008; the large amount of $t\bar{t}$ pairs produced will provide the opportunity to measure many top properties with a precision never reached before. Therefore the LHC accelerator can be considered as a real top quark factory compared to the Tevatron [1], where only few hundreds of events have been collected so far. Both ATLAS [4] and CMS [5] have conducted extensively studies in the top quark sector, trying to search for new physics by probing the SM. Moreover, $t\bar{t}$ events provide an excellent environment for calibration of the jet energy scale and b-tagging algorithms.

Among all the precision measurements in the top quark sector, the top quark mass plays a key role in constraining the SM: the Higgs boson mass is related to the other parameters of the model via loop corrections; since m_t is still the parameter with the largest experimental uncertainty, an improvement of its measurement will greatly reduce the allowed range for m_H . Together with the production cross section, this is the first important measurement to be performed, since any deviation from the SM can be interpreted as radiative corrections induced by new physics.

Another key aspect to investigate at LHC is the production of single top quark events: with an expected cross section of about 300 pb, a clean evidence of the production mechanism will open a new era of precision measurements in this field [6]. The single top quark cross section measurement will lead to the first direct measurement of V_{tb} at the few percent level of precision.

In addition, heavier particles in many scenarios beyond the SM decay into top quarks. For example, new resonances or gauge bosons strongly coupled to the top quark are expected in a large variety of models, in particular in strong ElectroWeak Symmetry Breaking (EWSB) [7, 8]. Preliminary evaluation of the sensitivity to a generic narrow resonance decaying into $t\bar{t}$ has been carried out to understand the effective capability of the LHC detectors to detect such signals.

This report is organized as follows. First a review of the potential use of top quark events as commissioning tools is described, focusing on jet energy scale and b-tagging performance evaluation. Then a summary of the realistic potential of CMS and ATLAS for the determination of the top quark properties from $t\bar{t}$ pairs and single top quark is given. Finally, an example of a search for a narrow resonance, decaying in $t\bar{t}$ events, illustrating the potentiality of new physics discoveries with top quarks, is discussed.

2 Commissioning with top quark events

A large amount of $t\bar{t}$ events will be produced at the LHC from the start. These events can be selected and used from the beginning for several commissioning tasks which are indispensable for a robust understanding of the ATLAS and CMS detectors.

Because of the high luminosity of the LHC, most of the measurements will be limited by the systematic uncertainty due to detectors effects. Each physics measurement at LHC uses mainly 5 detector objects: electrons, muons, photons, jets and missing E_T . For Jets and missing E_T , the most important systematic uncertainty is usually the energy scale. There are several proposals both from ATLAS and CMS, to measure these systematic effects directly from data and the top quark sector plays a strategic role in some of these proposals.

The high signal over background ratio in $t\bar{t}$ events allows to easily select a rich sample of b-jets where both energy scale of heavy-flavour jets and the b-tagging performance can be directly measured obtained from data.

Figure 1: The expected distribution of the three-jets invariant mass in a 100 pb^{-1} event sample

2.1 Light jet energy scale

An example of the initial “commissioning” analysis to identify $t\bar{t}$ events in ATLAS [9, 10], with a minimal set of cuts that don’t depend on a detailed understanding of the detector, imposes the following requirements:

- a good isolated lepton (electron or muon) with $p_T > 20 \text{ GeV}/c$;
- missing $E_T > 20 \text{ GeV}$;
- at least 3 jets with $p_T > 40 \text{ GeV}/c$ and a 4^{th} one with $p_T > 20 \text{ GeV}/c$;
- no b-tagging applied.

An iterative cone algorithm with $\Delta R = 0.4$ has been used for jet reconstruction and the analysis is limited to the central region of the detector ($|\eta| < 2.5$ for the lepton and the 4 jets).

The hadronic top quark candidate is defined as the three-jet combination with the highest transverse momentum. To improve the quality of the selection, at least one of the three di-jet invariant masses from the three hadronic top quark jets has to be within $10 \text{ GeV}/c^2$ of the reconstructed mass of the W boson. Additionally a top quark mass window is applied ($141 < M_{top}^{reco} < 189 \text{ GeV}/c^2$). For 100 pb^{-1} luminosity, 975 signal events (and 232 events from the W+jets background) survive the selection with a 43.3% purity. As can be seen from Figure 1, the top quark mass peak is clearly visible but it is shifted because no correction to the jet energy is applied. Moreover, since a correct estimation of missing E_T is difficult at start-up, the same selection procedure has been followed dropping the missing E_T requirement (Fig. 2).

The distribution of the masses of all di-jet combinations in the three-jet top quark candidate (with additional strong requirement on the W boson and top quark masses), can be used to select an enriched W boson sample. A careful study of this enriched sample, together with the well known W boson mass value, allows to extract a set of corrections to the light quark jet energy scale.

Semi-leptonic decays of $t\bar{t}$ events provides thousands of light jets from W decays. The CMS collaboration presented a method to extract the absolute jet energy scale corrections by using the accurately known value of the mass of the W boson [11].

2.2 Calibration of b-tagging efficiencies

Various btagging algorithms have been implemented for CMS and ATLAS, and their performance has already been studied with dedicated Monte Carlo simulations [12, 13]. The efficiencies and purities of these algorithms,

Figure 2: The expected distribution of the three-jets invariant mass in a 100 pb^{-1} event sample, without application the missing E_T request

however, will have to be calibrated once the detectors start taking data. A new method to calibrate b-tagging algorithms using a b-enriched data sample obtained from semi-leptonic $t\bar{t}$ events has been proposed within the CMS collaboration [14].

A global discriminator variable to identify the muon (electron) from $W^\pm$ decays in $t\bar{t}$ events has been created, combining isolation variables from calorimeters, tracker information (and muon chambers for the muon case) and the association significance to the primary vertex. At least four jets (iterative cone algorithm, $\Delta R = 0.5$) with $p_T > 25 \text{ GeV}/c$ are requested. A cleaning procedure to reject jets which are not coming from the primary vertex has been also implemented (using the tracks associated to the jets) to improve the quality of the selection.

A kinematic fitting procedure is finally applied to the event to fully identify the topology of the event. As a result of the fit, a χ^2 probability is returned if the fit converged, along with the vectors of the fitted objects. To improve the signal over background ratio, a loose b-tag is applied to the b-jet of the hadronic top quark for each solution to the event reconstruction.

To extract a b-enriched jet sample from the selected events, only the b-jet coming from the leptonically decaying top quark can be used, because one jet was already tagged as a b-jet in the system of the hadronically decaying top quark. Several observables were identified that discriminate between good jet associations and combinatorial background. Examples of these variables are the transverse momenta of fitted objects, angles between them, the χ^2 probability of the kinematic fit, the mass difference of the hadronically decaying top quark before and after the kinematic fit, etc. A likelihood method combining these observables has been finally used to increase the b-jet content of the jet sample.

From this jet sample, a simple technique was used for the actual measurement of the b identification efficiencies using the fraction of b/light jets in the sample, estimated from Monte Carlo simulations. A detailed study of systematic effects has been carried out, showing that the main systematic effect is the uncertainty on b purity in the jet sample. A similar procedure has been also applied to the fully-leptonic $t\bar{t}$ events to increase the data sample. In Figure 3 the combined expected uncertainty on the b-tagging efficiencies in the barrel ($|\eta| < 1.5$), is shown as a function of the E_T of the jets.

3 Top quark mass and cross section determination

In the commissioning phase, both ATLAS and CMS will measure the $t\bar{t}$ cross-section and the mass in the semi-leptonic channel with a relative small uncertainty (few percent for the mass and $\approx 10\text{-}15\%$ for the cross section). A long-term program to reach the level of $1 \text{ GeV}/c^2$ uncertainty on the m_t determination is however planned.

Figure 3: The combined expected uncertainty on the b-tagging efficiency in the barrel ($|\eta| < 1.5$), as a function of the E_T of the jets

Several methods have been explored for different final state topologies and the studies have shown that the expected uncertainty, for a luminosity of 10 fb^{-1} , on the mass measurement could reach this goal if detectors and theoretical systematic uncertainty are well under control [15, 16, 17]. A similar program for the cross section also exists, but the systematic uncertainty is at present limited to $\approx 10\%$ because of the currently relatively large uncertainties on b-tagging algorithms and the luminosity.

Among the large list of systematic contributions that enter the mass and cross-section measurements, the major effects (depending on the decay channel) are summarized in the following list:

- light and b-jet energy scale;
- initial/final state radiation modeling;
- minimum-bias and underlying events estimation;
- parton distribution functions;
- uncertainty on b-tag performances.

For example, to reach the precision of $1 \text{ GeV}/c^2$ on the top quark mass using the semi-leptonic $t\bar{t}$ events, a 1.5% uncertainty is needed on the b-jet energy scale calibration. The light-quark jets can be calibrated directly from the W boson mass constraint as shown in [11]. Most of these systematic effects have to be extracted from independent data samples to have a robust and reliable evaluation. Both ATLAS and CMS have a detailed program during the initial period of data taking, to measure these effects directly from data.

4 Single top quark production

Production of top quark events at LHC is not limited to $t\bar{t}$ pairs. Indeed single top production via the s and t channel, as well as the associated production of a top quark and a W boson, account for a third of the overall production cross-section of top quarks at the LHC. The NLO total cross section for each process amounts to $\sim 10 \text{ pb}$, $\sim 250 \text{ pb}$ and $\sim 70 \text{ pb}$ respectively [6]. Because of the different final states and topologies, different selection strategies have to be developed and different analysis will be performed both in ATLAS and CMS. These measurements are in most cases dominated again by systematic uncertainties and enforce the need for early strategies devoted to the control of experimental bias, modeling effects and reliable background determinations. Indeed, the general systematic considerations accounted for the $t\bar{t}$ mass and cross-section measurements apply also to measurements with single top quark events.

A detailed overview of the ATLAS analysis for cross section measurement in single top quark production, reported in [18], shows that the t -channel analysis appears as the most favourable case due to its higher production cross section and better signal over background ratio. The precision that can be achieved with an integrated luminosity of 30 fb^{-1} is:

$$\frac{\Delta\sigma}{\sigma} = 1\%_{\text{stat}} \pm 11\%_{\text{exp}} \pm 6\%_{\text{thbkgd}} \pm 5\%_{\text{lumi}}$$

A similar result is quoted by a CMS analysis [19], which reports the following precision on the t -channel with 10 fb^{-1} of integrated luminosity:

$$\frac{\Delta\sigma}{\sigma} = 2.7\%_{\text{stat}} \pm 8.1\%_{\text{syst}} \pm 3\%_{\text{lumi}}$$

The measurement of the cross sections are directly related to the $|V_{tb}|$ matrix element in the CKM matrix. If the SM holds, stringent limits on couplings of new interactions can be established using the measurement of the t -channel cross section.

5 Search for new physics

The much higher mass of the top quark with respect to the other fermions suggests a strong connection with the mechanism of the EWSB. Any new physics in EWSB models would be coupled preferentially to the top quark, leading to deviations from the SM, both in top quark production and decays.

Figure 4: 5σ discovery potential of a narrow $t\bar{t}$ resonance in ATLAS: $(\sigma \cdot Br)_{res}$ (plain line) and $(\sigma \cdot Br)_{res}^{min}$ (dotted line)

A preliminary evaluation of the sensitivity to a generic narrow resonance decaying into $t\bar{t}$ has been carried out by the ATLAS experiment [20]. The goal was to determine the 5σ discovery potential of a generic Technicolour resonance (spin-0 meson, electroweak singlet and QCD colour octet) with mass between 400 and 5000 GeV/c^2 .

A sliding window over the invariant mass spectrum has been used to estimate the discovery potential, applying a standard selection and reconstruction procedure similar to the one used for semi-leptonic $t\bar{t}$ events. The result of the study is shown in Figure 4 for an integrated luminosity of 30 and 300 fb^{-1} . The value of $(\sigma \cdot Br)_{res}^{min}$ (corresponding to at least 10 signal events around the resonance mass), together with $(\sigma \cdot Br)_{res}$, is plotted as a function of the resonance mass; for a mass above 2.5 - 3.0 TeV, the discovery limit $(\sigma \cdot Br)_{res}$ reaches the lower limit $(\sigma \cdot Br)_{res}^{min}$ because only few SM $t\bar{t}$ pairs are produced with these invariant masses.

6 Conclusions

Precision measurements in the top sector depend on the knowledge of several important detector-related systematic effects. These effects can often be measured directly from data using many techniques developed by ATLAS and CMS collaborations. Moreover $t\bar{t}$ events would play an important role in the first phase of the LHC startup, where the main concern will be to measure these effects and tune Monte Carlo simulation accordingly.

The sensitivity to new physics beyond the SM using $t\bar{t}$ and single top quark events depends on such knowledge and it is a crucial task during the first year of data taking to improve both theoretical and experimental uncertainties. Due to the large statistics expected at the LHC, most measurements will be dominated by the systematic uncertainties.

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