Vol. 38 (2007) *ACTA PHYSICA POLONICA B* No 2

TOP PHYSICS DURING FIRST LHC RUNS*

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(Received November 15, 2006)

At the LHC, millions of top quark pairs will be produced each year and already during the first LHC runs, a large and clean sample of them can be selected. The properties of the top quark can be extracted with great precision and with one of the most complex event topologies predicted by the SM, it will play an essential role during the detector commissioning phase. Understanding the detector response in such events in this new energy regime early during LHC operation is essential when searching for predicted signals from new physics models.

PACS numbers: 14.65.Ha

1. Introduction

In the Standard Model (SM) the top quark has a special place among the constituents of matter. It is by far the heaviest fermion and it is expected to play a special role in many extensions of the SM. The only place to study top quarks today is at the Tevatron collider, where the limited number of top quarks and substantial backgrounds make the measurement of its properties a challenging exercise. At the LHC, millions of top quarks pairs will be produced each year. This wealth of statistics opens a new era in top quark physics and allows to determine the properties of the top quark to high precision.

Although at the presently accessible energies elementary particle interactions are well described by the SM most particle physicists believe that the SM, with a single elementary scalar particle (the Higgs boson) cannot be the full story. The model has some fundamental limitations and is unable to answer a number of fundamental questions in physics today. Several

* Presented at the "Physics at LHC" Conference, Kraków, Poland, July 3–8, 2006.

models claim to solve some of the existing problems using a more fundamental description of nature, thereby predicting an unprecedented variety of (sometimes very spectacular) new phenomena.

Although there is no preferred extension, many have in common that they introduce new particles or interactions that can be observed by studying particle interactions at energies accessible at the LHC. With a typical combination of large amounts of missing energy, multiple lepton(s) and jets, the predicted experimental signatures are complex. Before claiming the observation of a signal from new physics in such topologies it is important to demonstrate that the detector response is also understood in these events. Top quark pair production has a (well predicted) experimental signature that is similar to that predicted by many of the new models and since top quark pairs are produced abundantly they form the ideal calibration channel. The well known combination of several high-level objects such as b-quark jets, isolated leptons, missing energy and jets from W-boson decays are key ingredients in most physics analyses.

Studying events that look like top quarks brings sensitivity to predictions from several new models simultaneously and creates an experimental environment from which it is possible to discover the first signs of the breakdown of our current understanding of particle interactions ... and a first glimpse of the fundamental physics that takes over.

2. Top production at the LHC

The cross section for $t\bar{t}$ production has been computed up to NLO and yields a cross section of around 750 pb at 14 TeV [1]. With almost a million top quark pairs per fb^{-1} of integrated luminosity the LHC is truly a top factory and already early in LHC operation top quark physics will not be limited by statistics.

In the SM, once produced, a top quark decays for nearly 100% into a b-quark and a W-boson. The W-boson then decays either into a pair of light, *i.e.* non-b, quarks ($\sim \frac{2}{3}$) or into a lepton and neutrino ($\sim \frac{1}{3}$). The 30% of events where one W-boson decays hadronically (2 jets) while the other decays leptonically (muon/electron and a neutrino): $t\bar{t} \rightarrow WbWb \rightarrow (l\nu)b(jj)b$ is called the *golden channel* as it has a very characteristic experimental signature (as is shown in Fig. 1) that allows to obtain a clean sample of top events. Semi-leptonic top events have:

- An (isolated) high-momentum electron or muon.
- An unbalanced visible momentum distribution in the plane transverse to the beam axis due to the neutrino that escapes detection.

- Four high-momentum jets, of which two jets originate from the decay of a W-boson and two jets that originate from b-quark fragmentation.

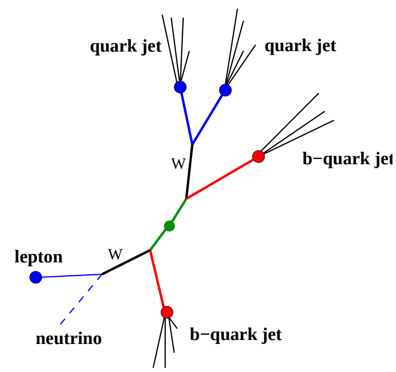

Fig. 1. Schematic event topology of a semi-leptonic top quark event.

A clean sample of top quarks can be selected by requiring the presence of an isolated high p_{T} lepton, large amount of missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) and at least 4 high p_{T} jets of which one or two are required to be identified as originating from b-quark fragmentation (b-jets). In addition, the invariant mass of the two non-b jets is required to be close to the mass of the W-boson. As almost no other SM processes can mimic this final state very little background remains and a $S/B \sim 80$ can be achieved [2]. Both the ATLAS and CMS experiment have developed extensive analyses to extract the properties of the top quark. An overview of CMS' top mass measurement plans are summarised by M. Duda elsewhere in these proceedings.

3. Selecting a clean sample of top quarks in early LHC operation

In preparing for early LHC operation, the ATLAS Collaboration has performed a so-called *commissioning analysis* [3,4] in which the identification of b-quarks is not required to be operating at its full potential. In fact, in the analysis b-tag information is not used at all. The commissioning analysis requires 4 jets (cone size $\Delta R = 0.4$) with $p_{\mathrm{T}} > 40$ GeV, an isolated lepton with a $p_{\mathrm{T}} > 20$ GeV and missing transverse energy exceeding 20 GeV. The dominant background at this stage comes from W+jets, a background that has been estimated using the `Alpgen` Monte-Carlo generator (4 jets inclusive sample) An effort to improve the background estimate from this process is ongoing using the MLM matching prescription. Without b-tagging the S/B level after these cuts is worse than the standard top analysis. The absence of b-jet identification introduces an additional ambiguity in the jet pairing (which three jets form the hadronic top quark). In the commissioning analysis the top quark is chosen as the set of three jets that has the highest vector sum p_{T}. The signal is further enhanced by requiring that at least one dijet combination within the group of jets has a mass close to that of the W-boson. The expected three-jet (top mass) distribution for an integrated luminosity of 100 pb^{-1} is shown in Fig. 2. The dominant background is from wrongly paired jets in true top quark events and it is clear that already during an early phase of LHC operation a large sample of top quark pairs can be isolated.

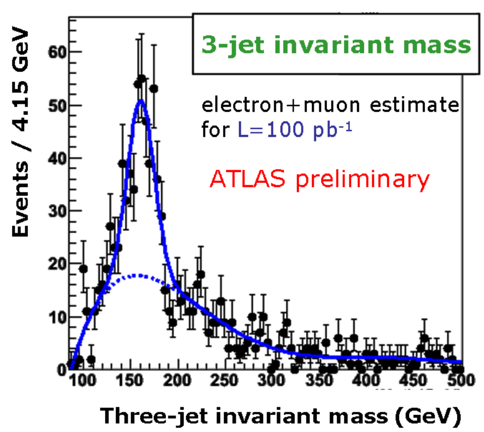

Fig. 2. The expected three-jet (top mass) distribution for an integrated luminosity of 100 pb^{-1} in the ATLAS commissioning analysis.

Several analysis improvements are under study. Relaxing the requirement on the minimum p_{T} of the 4^{th} jet in the event for example can potentially double the significance, but will require the careful evaluation and control of other sources of background. As is explained in Section 4 this event sample will play a vital role in understanding the detector in the commissioning phase and will provide a first window to new physics.

4. Calibrating the ATLAS detector in complex event topologies

When first proton–proton collisions start, each of the ATLAS sub-detectors has a detailed calibration and alignment programme to study the detector response to electrons, muons, photons and jets. This commissioning is done using well understood processes that have a simple topology (low particle multiplicity) like $Z \to e^+e^-$, $Z \to \mu^+\mu^-$ or Z/γ + jets. These calibrations do not, however, address issues that are specific to more complex collisions.

Under the hypothesis that events give top quark pairs, the event contains two equal-mass top quarks that have decayed into two b-jets and two W-bosons. These constraints can be exploited to calibrate the detectors in these environments:

- Calibrating the light jet energy scale.

  The absolute energy scale from the detector response to quark fragmentation can be calibrated using in each event the two jets that are known to originate from the decay of a W-boson, whose mass is known to high precision. The clean sample of top events and its variety of jet characteristics allow a detailed calibration of the light jet energy scale in a hadronic environment [5]. Problematic (combinations of) effects specific to these multi-jet topologies such as overlapping and/or fake jets make it difficult to extrapolate energy scale calibrations from simple topologies to this more complex environment.

- Missing energy from particles that escape detection.

  In some SUSY models the lightest SUSY particle is stable and escapes detection resulting in a large energy imbalance in the plane transverse to the beam axis. A reliable estimate for this quantity requires detailed knowledge of the calorimeter response. The missing energy can be calibrated to a good precision by using the fact that in top quark pair production the lepton and the missing energy vector (the neutrino) originate from the decay of a W-boson.

- Obtaining an enriched b-jet sample.

  Identification of b-jets is crucial in many analyses at the LHC. To perfect the various algorithms it is important to not have to rely on extrapolations from 'easy' calibration channels to the more complex event topologies where the b-identification algorithms will usually be applied. A correctly reconstructed top quark event contains *a priori* two b-jets and since the invariant mass of the two light jets is known to be close to that of the W-boson, an enriched sample of b-jets can be selected kinematically. The performance of the various b-identification algorithms can then be tested in complex events [6].

The large and clean sample of top quark pairs can be used as a first window to signals for *new physics* as is explained in Section 5.

5. Top quark signal as a window to new physics

The search for evidence of signs of new physics can take several directions starting from the clean sample of selected events that look like top quark pair production. Looking for deviations from the SM prediction allows to be sensitive to predictions from several new models simultaneously.

5.1. Anomalous top quark production: $pp \to X \to t\bar{t}$

In the SM, top quark pairs are mainly produced through gluon fusion and the distribution of the invariant mass from the top quark pair is determined by phase space (PDFs) only. Some models predict particles that can decay into a pair of top quarks. Effects from such non-SM top quark pair production could be observed in the invariant mass distribution of the top quark pair, either as a mass peak or as a deformation of the expected SM shape.
Resonances (mass peaks): Many models predict the existence of heavy particles or resonances ($Z', Z_H, G^{(1)}$ *etc.*) that can decay into a pair of top quarks. Their presence in the data will show up as a peak in the invariant mass distribution of the top quark pair. A search for such resonances is sensitive to several new physics models simultaneously and with 30 fb^{-1} of data, a resonance X can be discovered for a mass of 500 GeV/1 TeV/ 2 TeV if its cross section $\times \mathrm{BR}(X \to t\bar{t}) = 2560/830/160$ fb [2].
Deformations: Neutral Higgs bosons (SM or SUSY) can be produced through gluon fusion and can decay into top quark pairs. The diagrams that describe its production interfere with those from SM top quark pair production, predicting a distorted invariant mass spectrum for top quark pairs [7, 8]. The size and shape of the distortion depends on the mass and type of Higgs boson and the parameters that describe its decay. In Fig. 3 the invariant mass distribution of the top quark pair is shown for pure-SM production and that expected from several SUSY Higgs boson (H) mass hypotheses [8], revealing a dip-peak structure.

The size of the effect can be as large as several percent and with a width of 20 GeV(close to the experimental resolution) the effects could be observed early during LHC operation. If SUSY is discovered in another channel, the signal in the top sector can play a guiding role in reconstructing the parameters of the model. The measurement of $\sigma_{t\bar{t}}$ will be one of the first physics publications using LHC data and provides an independent estimate of the mass of the top quark [2] as $\sigma_{t\bar{t}}$ depends strongly on the mass of the top quark: $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} = 5 \times \Delta m_t/m_t$.

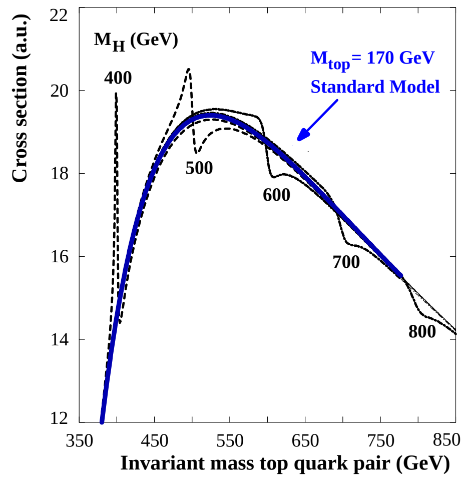

Fig. 3. The expected distribution of the invariant mass of top quark pairs for pure SM production (solid line) and for various SUSY Higgs boson mass hypotheses (dotted lines).

5.2. Events that are not top quark pairs: discovering SuperSymmetry

If SUSY particles exists at masses around a TeV, gluinos and squarks, the super-partner of gluons and quarks, will be copiously produced at the LHC. During their cascade decay they produce several high energetic particles and, if R-parity is conserved, also a pair of lightest super-symmetric particles that escape detection. With several jets, leptons and missing transverse

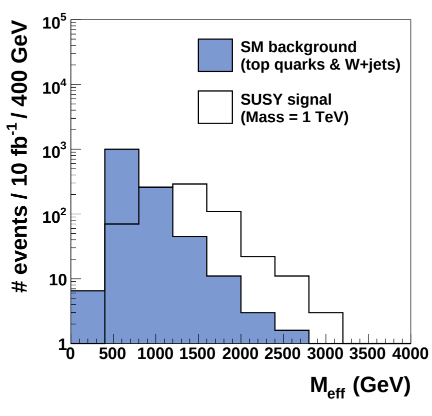

Fig. 4. The expected distribution of M_{eff} for SM events (solid histogram) and that from a SUSY signal (open histogram).

momentum these events have a topology similar to that of top quark pairs. Revealing the presence of these events is done by constructing a variable that is sensitive to the scale of the hard interaction: $M_{\rm eff} = E_{\rm T}^{\rm miss} + \sum_{\rm jets} P_{\rm T}^{\rm jet}$. The expected distribution of $\mathrm{M_{eff}}$ after 1 year of LHC operation has been evaluated for characteristic SUSY signals and SM processes in studies of the SUSY working groups. For ATLAS it is shown in Fig. 4, where the dominant SM contribution is from top quark pair production, whose characteristics are well understood as the detector can be calibrated using the large sample of other top quark pairs.

After one year of LHC operation sensitivity to a SUSY mass scale up to 2 TeV can be reached [9], covering a large part of the SUSY parameter space.

5.3. Rare top decays: FCNC's and charged Higgs boson production

In the SM flavour changing neutral currents (FCNC) are heavily suppressed. By searching for top quark decays to a Z-boson (or γ) and a light quark, the sensitivity to FCNC is increased by two orders of magnitude compared to the current limits from LEP/HERA experiments [2] and thereby close to the predictions from several extensions of the SM. If the Charged Higgs boson ($H^{\pm}$) is light enough, the top can also decay as $t \to H^{+}b$. Analyses [10] depend on the SUSY parameters that govern the decay of the charged Higgs boson.

6. Conclusions

The measurement of the top quark pair production cross section will be one of the early LHC physics goals (even without b-tagging) and together with measurement of the top properties (mass, width, charge, spin, *etc.*) top physics is a rich and interesting research programme at the LHC. During the LHC commissioning phase the top quark signal will play an important role in understanding the detector performance of the LHC experiments. The sample allows to calibrate light jet energy scales and to obtain a b-jet enriched collection of jets. Finally, top quarks also allow a detailed search for signs of new physics.

I would like to thank Marina Cobal, Anne-Isabelle Etienvre, Jerome Schwindling, Paul de Jong, Stan Bentvelsen, Wouter Verkerke, Jorgen D'Hondt and Steven Lowette for all their help when preparing this talk.

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