Studies of Top Quark properties at the LHC

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The LHC collider plans to start in 2007, after which millions of top quarks will be produced at the collision points. In the first period of data taking these events will provide an essential calibration tool for the ATLAS and CMS detectors. During a later stage, as part of the precision measurement programme, both detectors will determine the top mass and properties like spin, charge and couplings. Top physics also plays a central role in the search for new particles, both as source of a possible signal and as source of background.

1 Top quark physics

There are many motivations to study top quarks at LHC. It is by far the heaviest fundamental particle, with a mass close to the Electro-Weak Breaking Scale (EWBS). Precise determination of its mass allows stringent tests on the Standard Model (SM) and constrains via radiative corrections the mass of the Higgs boson. In many scenarios beyond the SM heavier particles decay into top quarks. Studying detailed properties of top quarks can give handles on new physics.

However also from the experimental point of view top quarks are important. Since they are abundantly produced at LHC, they provide an essential tool for understanding the detectors during the commissioning phase. Triggering, tracking, $b$-tagging, energy and jet calibration can all benefit from the present top signal.

Lastly, top quarks will be a major source of background for almost all searches for physics beyond the SM. Precise understanding of the top signal is crucial to claim new physics.

The cross section for $t\bar{t}$ production has been calculated up to NLO order, and results in $830 \pm 100 \text{ pb}^{-1}$, where the uncertainty reflects the theoretical error obtained from varying the renormalisation scale by a factor of two. With a luminosity of $10 \text{ fb}^{-1}$ in the first years of LHC running, and reaching $100 \text{ fb}^{-1}$ at the higher luminosity stage, top physics will hardly be limited by statistics.

The partonic center of mass (CM) energy $\sqrt{s}$ has to exceed twice the top mass $m_t$, and therefore the production dominates at $\hat{s} = x_1 x_2 \sim (350 \text{ GeV})^2$, which corresponds to $x_1 x_2 \sim 10^{-3}$ for the LHC CM energy of 14 TeV. The gluon density of the proton dominates at these values of $x$ and about 87% of the $t\bar{t}$ pairs is expected to be produced by gluon fusion, while the remaining 13% via quark-anti-quark annihilation. At the Tevatron, with a CM energy close to 2 TeV, the $t\bar{t}$ cross section is approximately a factor of 100 smaller, and the bulk of $t\bar{t}$ pairs are produced via the quark-anti-quark annihilation process).
The inclusive lepton plus jet channel, $t\bar{t}\rightarrow WWb\bar{b} \rightarrow (l\nu)(jj)(b\bar{b})$, provides a large and clean sample of top quarks and is the most promising channel for an accurate determination of the top quark mass.\(^2\) Considering only electrons and muons, the branching ratio of this channel is 29.6%. Various methods have been exploited to measure the top quark mass. In the most straightforward method the hadronic part of the decay is used, and the top mass is obtained from the invariant mass of the three jets coming from the same top: $m_t = m_{jjb}$.

The typical selection of single lepton top events is based on the presence of an isolated high $p_T$ lepton with $p_T > 20$ GeV and missing energy $E_{T}^{miss} > 20$ GeV. At least four jets, typically reconstructed with a cone size of $\Delta R = 0.4$, with $p_T > 40$ GeV and $|\eta| < 2.5$ are required. One or two jets are required to be tagged as $b$-jets. The reconstruction of the decay $W \rightarrow jj$ is first performed by selecting the pair of non-$b$-tagged jets with invariant mass closest to $m_W$. Events are retained only if $|m_{jj} - m_W| < 20$ GeV. The combination of the jet pair $jj$ with the $b$-tagged jet yields a combinatoric ambiguity. For events with only one tagged $b$-jet the events are kept for which the opening angle of the $b$-jet with the $W$ is smaller than with the lepton of the event. For events with two $b$-tagged jets, the $b$-jet which resulted in the highest $p_T$ of the system was combined with the jet pair $jj$.

![Figure 1: Reconstructed top mass for the CMS (left) and ATLAS (right) collaborations, for 10 fb$^{-1}$ of data.](image)

In Figure 2 the reconstructed $m_t$ for the ATLAS and CMS detectors is shown. The statistical uncertainty on the top mass is not a problem and the background is well under control, with a signal to background ratio $S/B \sim 65$.

The largest systematic uncertainties arise from the jet energy scale, the $b$-quark fragmentation, the initial and final state radiation and the background contributions. The studies indicate that a total error on $m_t$ below 2 GeV should be feasible, possibly reaching an ultimate precision around 1 GeV.

Already in the commissioning phase of the detectors, during the startup of LHC, it will be possible to observe a top signal. ATLAS performed a study in which $b$-jet tagging is assumed to be absent, as pessimistic scenario. In this case the top mass is reconstructed from a sample of events with exactly four reconstructed jets and the three jets which result in the highest invariant $p_T$ are used to calculate the invariant mass. Figure 2 shows the expected signal for a luminosity of 150 pb$^{-1}$, i.e. after a few days of running. The most important background, production of $W + 4$ jets, is determined from matrix element calculations using the AlpGen event generator, whereas the signal is obtained from the NLO Monte Carlo generator MC@NLO.
Figure 2: Reconstructed top mass, without b-jet tagging, for 150 pb$^{-1}$ of data. The background corresponds to $W+4$ jet events.

3 Top properties

The high statistics available at LHC, will allow to study many properties of the top quark. In order to confirm that its electric charge is indeed $Q_{\text{top}} = 2/3$, one can either measure the charge of the $b$-jet and the $W$ boson, or attempt to directly measure the top quark coupling through photon radiation in $pp \to t\bar{t}\gamma$ and $pp \to t\bar{t}$ with $t \to Wb\gamma$. Since the first process is dominated by $gg$ fusion at LHC, one expects that the $t\bar{t}\gamma$ cross section is approximately proportional to $Q_{\text{top}}^2$.

The treatment of the radiative top production and top decay matrix elements, fed into the Pythia Monte Carlo, was based on the on-mass approach for the decaying top, i.e. the production and decay were treated independently. By suitable selection criteria the hard $\gamma$ radiation from top production can be enhanced. It is foreseen to disentangle the top charge during the first year of running at LHC using this method.

The $t\bar{t}$ spin correlations allow the direct measurement of the top quark spin. In the dileptonic $t\bar{t}$ channel the helicity angles $\theta^*$ of the leptons are given by the double differential cross section

$$\frac{1}{\sigma_{\text{tot}}} \frac{d^2\sigma}{d\cos\theta^*_+ d\cos\theta^*_-} = \frac{1}{4} (1 - A \cos\theta^*_+ \cos\theta^*_-)$$

(1)

with the asymmetry $A$ in the helicity basis defined as the normalized difference between like-spin and unlike-spin top pairs. At the LHC where $gg$-fusion dominates, the asymmetry is expected to be $A = 0.31 \pm 0.03$. Studies are underway to determine also in semi-leptonic top events the top spin correlations. In these studies the softest jet is used as spin analyzer.

4 Exotic models

Due to its large mass, the top quark could be part of massive particle decays. Its clear experimental signature makes it a very interesting tool to study the exotic decays. Some examples include: "Heavy top" in Little Higgs models, signatures which include the quark top in models with extra-dimensions, search of resonances which decay in $t\bar{t}$ (as predicted in SM Higgs, MSSM Higgs, Technicolor models, strong electroweak symmetry breaking models, Topcolor, etc.). Physics beyond the SM could affect cross section measurements for $t\bar{t}$ production in a variety of ways: a heavy resonance decaying to $t\bar{t}$ might enhance the cross section, and might produce a peak in the $t\bar{t}$ invariant mass spectrum. Because of the large variety of models and their parameters, in ATLAS a study was made of the sensitivity to a "generic" narrow resonance decaying to $t\bar{t}$. Events of the single lepton topology were selected. In addition, between four and ten jets were required with $p_T>20$ GeV and $|\eta|<3.2$, with at least one of them tagged.
as $b$-jet. After these cuts, the background is dominated by the $t\bar{t}$ continuum. The obtained mass resolution $\sigma(m_{t\bar{t}})/m_{t\bar{t}}$ was equal to 6.6%. As an example, Figure 3 shows the reconstructed $m_{t\bar{t}}$ distribution for a narrow resonance of mass 1600 GeV.

![Graph showing mass resolution and branching ratio](image)

**Figure 3:** On the left: Measured $m_{t\bar{t}}$ invariant mass distribution for reconstruction of a narrow resonance of mass 1600 GeV decaying to $t\bar{t}$. On the right: Value of $\sigma \times BR$ required for a 5$\sigma$ discovery potential for a narrow resonance decaying to $t\bar{t}$, as a function of $m_{t\bar{t}}$.

The reconstruction efficiency, not including BRs, was about 20% for a resonance of mass 400 GeV, decreasing gradually to about 15% for $m_{t\bar{t}} = 2$ TeV. For a narrow resonance $X$, fig. 4 shows the required $\sigma \times BR(X \rightarrow t\bar{t})$ for a discovery (the signal must have a statistical significance of at least 5$\sigma$ and must contain at least 10 events). Results are shown as a function of $m_X$ for integrated luminosity of 30 fb$^{-1}$ and 300 fb$^{-1}$.

5 Rare decays

With its large mass, the top quark will couple strongly to the EWSB sector. Many models of physics beyond the SM include a more complicated EWSB sector, with implications for top quark decays. Example includes the possible existence of charged Higgs bosons, or possibly large flavour changing neutral currents (FCNC) in top decays. In the SM, FCNC decays of the top quark are highly suppressed ($BR < 10^{-13}$-$10^{-10}$). However, several extensions of the SM can lead to very significant enhancements of these BRs ($10^{-3}$-$10^{-2}$ or even higher). The sensitivity to some of these scenarios has been investigated by both ATLAS and CMS.

In particular the FCNC processes $t \rightarrow Zq$, $t \rightarrow \gamma q$, $t \rightarrow gq$, $t \rightarrow WbZ$, $t \rightarrow WbH$, $t \rightarrow Hq$ have been studied. It has been shown that the limit on the branching ratios of these processes can be improved by orders of magnitude with respect to the current limits, and will range from $10^{-7}$ for $t \rightarrow WbZ$ to $10^{-3}$ for $t \rightarrow gq$ using 100 fb$^{-1}$ of data.

6 Single top production

The precise determination of the properties of the $W$-$t$-$b$ vertex, and the associated coupling strengths, will more likely be obtained from measurements of the electroweak production of single top quarks. Single top quarks can be produced via three different reactions (shown in Figure 4): $W$-gluon fusion ($\sigma \simeq 250$ pb), $Wt$ production ($\sigma \simeq 60$-$110$ pb) and $W^*$ process ($\sigma \simeq 10$ pb). There are important backgrounds with final states similar to the signals under study (e.g. $\sigma(tt) = 830$ pb, $\sigma(Wb\bar{b}) > 300$ pb) and the possibility to extract a signal depends critically from the detector performance. Important parameters are the rate of fake leptons, the $b$-jet identification and fake $b$-jet rate, the capability to identify forward jets and to veto low energy jets. To reduce the enormous QCD multi-jets background, the $t \rightarrow 1\nu b$ decay has been studied, and a pre-selection was done in which a high $p_T$ lepton, at least two jets, at least one $b$-tagged jet, and one forward jet are required. It is interesting to study the three processes separately,
Figure 4: Feynman diagrams for the electroweak single top quark processes accessible at the LHC: a) $W$-gluon fusion, b) $Wt$ production, c) s-channel or $W^*$ process.

since they have separate sets of backgrounds, their systematic errors for $V_{tb}$ are different, and they are differently sensitive to new physics. For example, the presence of a heavy $W$ would result in an increase of the $W^*$ signal. Instead, the existence of a FCNC $g u \to t$ would be seen in the $W$-gluon fusion channel. Discriminants for the three signals are for example: the jet multiplicity (higher for $Wt$), the presence of more than one jet tagged as a $b$ (this increase the $W^*$ signal with respect to the $W$-gluon fusion one), the mass distribution of the 2-jet system (which has a peak near the $W$ mass for the $Wt$ signal and not for the others).

The results found for the relative experimental statistical errors on the production cross sections of the single top processes, imply statistical uncertainties on the extraction of $V_{tb}$ of 0.4% for $W$-gluon fusion, 1.4% for $Wt$ and 2.7% for $W^*$. The errors in the extraction of $V_{tb}$ would be dominated by uncertainties in the theoretical predictions of the cross-sections. These arise from uncertainties in the parton distribution structure functions (PDFs), uncertainty in the scale ($\mu$) used in the calculation, and the experimental error on the top mass, and amounts to approximately 6% for all three processes.

7 Conclusions

At LHC, the top mass will be determined with an ultimate precision of approximately 1 GeV. However, already during the commissioning phase of the LHC the top quark signal will be observed using simple and robust reconstruction methods.

The high statistics sample will allow to determine top quark properties like charge and spin unambiguously. Exotic models involving top will be tested with high precision. Limits on rare FCNC top decays will be improved by orders of magnitude, or even observed experimentally. The observation of single top production will allow a precise determination of $V_{tb}$.

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