SM Top properties at LHC: top charge, Branching Ratio and top pair production associated with gauge bosons

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Abstract. In this contribution, we review some of the properties of the top quark in LHC measurements by the CMS and ATLAS Collaborations using pp collisions at 7 TeV. Firstly, measurements of two intrinsic properties of the top quark are revisited: its charge and branching ratio. Then, the first measurements of associated production of top pairs with electroweak gauge bosons W, Z and photons are presented. Associated production cross-sections provide information on the structure of the electroweak couplings to top quarks. All measurements are consistent with the expectations from the standard model top properties.

1. Introduction

With the LHC data from pp collisions at 7 TeV collected in 2011 using ATLAS and CMS detectors a new level of understanding on the properties of the top quark was achieved. Some of the experimental results from the Tevatron collider could be verified at much better precision, and new measurements which were not accessible at the Tevatron became possible with these data.

We review a few results from top measurements by the CMS and ATLAS Collaborations. A detailed description of the ATLAS and CMS detectors can be found elsewhere [1, 2]. The measurements of special interest are those which can potentially indicate the existence of physics beyond the standard model (SM).

One of the intrinsic properties of the quark top, its electric charge, was investigated under the possibility of an exotic scenario in disagreement with the SM.

Properties of the top decay are also an excellent testing ground to the SM. In particular, deviations from the SM prediction of top quarks decaying almost exclusively in the mode $t \rightarrow Wb$ can be indicative of a fourth quark generation. We present measurements by the CMS Collaboration on the decay rates of top quarks to b and light quarks. Experimental results concerning other properties of the top quark decay are covered in other contributions to this conference.

The production of $t\bar{t}$ associated to gauge bosons are of special interest in the LHC physics program since their cross-sections are too low to be measured with high precision at the Tevatron. Properties of $t\bar{t}$ couplings to bosons can be inferred from the cross-sections and...
angular distributions observed in such processes. Measurements of \( \tau \bar{\tau} \gamma \) from the ATLAS and \( \tau \bar{\tau} V \) (where \( V=W, Z \)) from the CMS Collaborations are presented. The search for \( \tau \bar{\tau} \) associated to the Higgs boson was presented in another session in this conference, and is not reported here.

2. Top electric charge

The top quark decays mainly to a \( W^+ \) boson and a b-quark. As the electroweak isospin partner of the b-quark, its expected electric charge in the SM is \( +2e/3 \). In an exotic scenario where this hypothesis does not hold, the top charge could assume the value of \(-4e/3\), decaying instead to a \( W^- \) boson and a b-quark.

The measurements of the top electric charge \([3, 4]\) at the LHC were performed using semileptonic \( \tau \bar{\tau} \) decays. If one of the W bosons decays leptonically (i.e. to a neutrino and an electron or muon), its charge can be directly measured as the charge of the electron or muon. The challenging aspects of the measurement are, then, to perform the correct association of the b-quark and the W to its parent top, and determine the electric charge of the other top decay product, the b-quark.

The identification of jets initiated by b-jets (b-tagging) is based on the properties of the B hadrons. Due to the long B lifetime, a b-jet is produced typically with large impact parameter as compared to a light quark- or gluon-initiated jet. For this reason, information related to the impact parameter or the tracks from secondary vertices inside the jet can be combined into variables with discriminating power to separate b- from light quarks- or gluon-initiated jets. B-hadrons also decay into leptons, thus some discriminators rely on the detection of non-isolated low-\( p_T \) ("soft") muons, and use parameters such as the soft muon \( p_T \) relative to the jet axis.

Two techniques were used to determine the charge of the b-quark. The first relies on the charge of the soft muon coming from the B-hadron decay. In direct B-hadron decays, the charge of the soft muons is the same as the b-quark. However, in the cases of flavour oscillations and B-hadron cascade decays, such as \( b \rightarrow D^+X \rightarrow \mu^+\nu X \), the charges of the muon and b-quark are not necessarily the same, degrading the measurement. In the second method, a "jet charge" \( Q_{b\ jet} \) is assigned according to the momentum-weighted sum of the charges \( q_i \) of all jet tracks

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Q_{b\ jet} = \frac{\sum |\vec{p}_{T_i}| \cdot \kappa}{\sum |\vec{p}_{T_i}|},
\]

where \( \vec{j} \) is the jet axis direction and the parameter \( \kappa (=0.5 \) and \( =0.7 \) for the analysis by ATLAS and CMS, respectively) is optimized for the best separation between b and b jets.

The charge of the b-jet estimated with one of the described methods is combined with that of the lepton from the W decay to determine the charge of the top quark, and compared to the expectations from the SM and the exotic scenario. Both experiments exclude an exotic scenario at 5 \( \sigma \), confirming at the LHC the top charge constraints found previously at the Tevatron \([5]\).

3. Branching Ratio

CMS has measured \([6]\) the ratio of the Branching Ratios (BR) \( R = B(t \rightarrow Wb)/B(t \rightarrow Wq) \) where B(\( t \rightarrow Wb \)) is the BR of the top decaying to b's and B(\( t \rightarrow Wq \)) the BR of the top decaying to light quarks. A high-purity \( \tau \bar{\tau} \) sample in the full-leptonic decay mode, corresponding to 2.2 fb\(^{-1}\), was used. As in the case of the electric charge measurement, the measurement requires the correct identification of b and light quarks, and correct association to its parent top.

The ratio was measured using a model based on 3 parameters: the b-tagging efficiency, the efficiency for the b-tagging criteria to accept light jets (mistags), and the fractions of events with two, one or no top quarks reconstructed and selected.

Events were none or only one top is correctly reconstructed correspond to background events or to \( \tau \bar{\tau} \) events where at least one of the jets is missed and the top is reconstructed with a wrong choice of jet. Single-top events correctly reconstructed also contribute to the "one top" category. The number of top quarks with misassigned jets was estimated in data using the
distribution of the invariant mass of the lepton-jet pairs. Distributions of wrongly reconstructed jets were built rotating the components of the b-jet momentum, or using in the reconstruction a b-jet of another event. For top quarks correctly reconstructed, the distribution is expected to fall-off around \(\sqrt{m_t^2 - m_W^2} = 156 \text{ GeV}/c^2\); therefore, the wrongly reconstructed distribution can be normalized on the tails of the data distribution. This technique was applied in data and cross-checked in simulation, as shown in Fig. 1 (a). The two remaining parameters in the model, the efficiencies for b-tagging and mistags, were measured using a multi-jets (QCD) sample as described elsewhere [7].

The model for the observation of different b-tag multiplicities as a function of \(R\) and the multiplicities observed in the data, compared to the simulation, are shown in Fig. 1 (b) and (c), respectively. The measurement yields \(R = 0.98 \pm 0.04\), in agreement with the SM. If the requirement \(R \leq 1\) is imposed, the limit \(R > 0.85\) is obtained at 95% C.L.

**Figure 1.** (a) Invariant mass of the lepton-jet pairs in the inclusive dilepton channel: number of correct jet assignments (simulation), model for wrongly assigned jets and the sum (data and simulation). (b) Model for \(R\) as a function of the b-jet multiplicities. (c) Observed b-tag multiplicity in data and simulation.

4. Associated top pair production

ATLAS Collaboration has measured [8] the cross-section times branching ratio of the inclusive \(t\bar{t} + \gamma\) process using 1.04 fb\(^{-1}\). The sample is selected to contain semi-leptonic \(t\bar{t}\) decays to both electrons and muons. Additionally, a photon with \(p_T > 15\) GeV and selected according to a set of shower shape criteria was required. Photons irradiated both at top production and decay were considered as part of the signal. The signal to background separation is performed by fitting the data using templates for prompt photons and “fake photons”, which are hadrons in \(t\bar{t}\) events passing the full \(\gamma\) selection criteria. Promptly produced photons are mostly isolated and have similar shower shapes than electrons. Hadrons faking photons, on the other hand, are non-isolated. Signal templates are built from the data using the isolation variable as measured in \(Z \rightarrow \mu\mu\) events. The templates for “fake photons” are obtained on a sample selected using jet triggers. To avoid the presence of real photons, the events entering the “fake” template are required to fail one of the shower shape criteria applied for the signal. The results of the template fit is shown in Fig. 2. Although the fit was performed simultaneously to the electron and muon channels, results are shown separately for each channel.

The measured cross-section times BR for the \(t\bar{t} + \gamma\) process, for photons with transverse momenta \(p_T > 8\) GeV is \(2.0 \pm 0.5\) (stat.) \(\pm 0.7\) (syst) \(\pm 0.08\) (lumi) pb. The SM predicts \(2.1 \pm 0.4\)
pb for the same phase space and BR. Since the electromagnetic coupling of a fermion to photon depends on the fermion electric charge, this measurement can be interpreted as an alternative estimator of the top charge.

Figure 2. Template fits on the track isolation variable $p_T^{\text{cone20}}$, defined as the scalar sum of all tracks in a cone with $\Delta R < 0.20$ around the photon candidate. Results for (a) electrons and (b) muons.

In CMS [9], the associate production $t\bar{t}+V$, with $V=W$ or $Z$ was measured using two independent final states: firstly, trilepton final states with 4 jets, at least 2 of them b-tagged, and 3 leptons, at least 2 of them of the same flavor and opposite charge were considered. These requirements aimed to select events from the process $pp \rightarrow t\bar{t}Z \rightarrow (t \rightarrow b \nu j)(t \rightarrow b \nu)(Z \rightarrow ll)$, where $l$ is an electron or muon. Secondly, a sample containing at least 3 jets, one of which b-tagged, and two leptons of opposite charge was selected. With these criteria, events from both $pp \rightarrow t\bar{t}Z \rightarrow (t \rightarrow b \nu j)(t \rightarrow b \nu)(Z \rightarrow ll)$ and $pp \rightarrow t\bar{t}W \rightarrow (t \rightarrow b \nu j)(t \rightarrow b \nu)(W \rightarrow ll)$ processes are selected.

Both analyses are based on 5 fb$^{-1}$ of data. In order to guarantee statistical independence of the two analyses, events fulfilling the trilepton selection are vetoed in the dilepton analysis.

Multilepton final states are rare in the SM, so a substantial fraction of the background in both analyses are originated from misreconstruction effects, such as “fake” leptons and misidentified b-jets. The estimation of such background sources was perfomed on control samples of data with looser selection criteria and extrapolated to the fiducial region of each analysis. The number of observed events compared to background predictions in each channel is shown in Fig. 3(a) and (b) for the trilepton and dilepton selections, respectively.

The $t\bar{t}+Z$ cross section measured using the dilepton selection is $0.30^{+0.14}_{-0.11}\text{(stat)}^{+0.04}_{-0.02}\text{(syst)}$ pb, with a significance of 3.66 standard deviations and compatible with the NLO prediction of 0.1387 pb. In the trilepton channel, the measured $t\bar{t}+V$ cross section (where $V=Z$ or $W$) was $0.45^{+0.12}_{-0.10}\text{(stat)}^{+0.06}_{-0.05}\text{(syst)}$ pb, with a significance of 2.99 standard deviations.

The $t\bar{t}+Z$ cross section from the dilepton selection was extrapolated to an inclusive $t\bar{t}+V$ cross section, and combined to the cross-section measured using the trilepton selection, yielding a $t\bar{t}+V$ cross section of $0.51^{+0.15}_{-0.13}\text{(stat)}^{+0.05}_{-0.04}\text{(syst)}$ pb. The result is slightly above but still compatible with the NLO expectation of 0.308 pb. The results on $t\bar{t}+V$ from the individual and combined measurements is summarized in Fig. 3(c).

5. Conclusions

Measurements of the top properties using LHC pp data taken at 7 TeV in 2011 were presented. Top electric charge and flavour content of top decays were probed and found in agreement with the expectations from the SM. The low number of associated $t\bar{t}+\gamma$ and $t\bar{t}+Z$ events in 2011 data does not yet allow careful experimental study of the structure of the electroweak couplings to top quarks. In spite of the large uncertainties, the measurements performed by CMS and
ATLAS are still of interest in top physics, since they pave the way for more precise measurements in the near future. Moreover, these processes, as well as $t\bar{t}+W$, are important backgrounds on searches for new physics, as for instance SUSY searches, and to the measurement of associated $t\bar{t}+\text{Higgs}$ production.

Prospects for the top physics program in the near future are promising. CMS and ATLAS have arrived at the end of 2012 with reconstructed data corresponding to more than 20 fb$^{-1}$ of integrated luminosity per experiment, taken at a higher collision energy than in 2011, $\sqrt{s}=8$ TeV. Even more data was collected and stored (via Data Parking at CMS and the Delayed Data Stream at ATLAS), that should be available to be analyzed in 2013. This unprecedented amount of data from high-energy pp collisions will bring important improvements to the precision of the top quark properties measurements. Direct improvements will be obviously seen in the studies involving rare processes (statistically limited in 2011) such as the associated productions of $t\bar{t}+(\gamma,W,Z$ and Higgs). In all top measurements, the reduction on some of the systematic uncertainties, such as background estimation using data, is also expected.

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