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# Top and top-pair mass measurement at CMS

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**Abstract.** In this article the measurements of the top mass and the top-pair mass by using  $t\bar{t}$  events produced in proton-proton collisions at 7 TeV with the CMS detector at the LHC [1] are presented. Particular emphasis will be given to the reconstruction challenges involving jets in the final state. The presented results correspond to the data collected by CMS in 2010 and an integrated luminosity of 36/pb.

### 1. Introduction

Top physics is one of the pillars of the physics program at the LHC. The top quark is the heaviest elementary particle known and is strongly coupled with the electroweak symmetry breaking sector. Indeed, the top mass is a fundamental parameter of the Standard Model (SM) whose precise knowledge greatly helps in constraining the model itself and in determining indirect constraint on unknown parameters, like for instance the Higgs boson mass. Moreover, top pair production is the perfect window for finding evidence of new physics: several models even predict favourable couplings of new particles to the third family.

Doing top physics at a hadron collider requires a throughout understanding of the detector and complex analysis tools. Depending on the decay of the W bosons, top pair production always leads to jets in the final state, and may also involve the production of charged leptons and neutrinos, originating missing transverse energy. The understanding of the hadronic component is therefore crucial for a full event reconstruction: in the following we will try to underline the aspects which are more important for a measurement, namely the impact of the knowledge of the jet energy scale, the jet pairing, heavy flavour tagging, and top tagging for boosted objects.

#### 2. The top mass in the dilepton channel

The first measurement of the top mass at the LHC has been performed by CMS by using the di-lepton final states. In spite of a lower branching ratios and a more difficult reconstruction procedure, due to the presence of two neutrinos in the final state, the di-lepton channel is much more background free and the event selection straightforward. The event is required to contain two isolated, prompt, opposite charge leptons with  $p_T > 20 \text{GeV/c}$  and pseudorapidity  $|\eta| < 2.5$ . For same flavour leptons a mass window of 15 GeV/c<sup>2</sup> around the Z mass is vetoed. Jets are built from the individual particles reconstructed in the detector, matching the information from all the subdetectors CMS is composed of [2]. At least two jets with  $p_T > 30$  in the central detector region are required, and a cut on the missing transverse energy at 20 GeV (30 for same flavour lepton final states) is imposed. With a statistical sample of 36/pb, a total of 102 events have

been selected, to be compared to 108.5 expected from MC, with an expected purity of about 90%.

For determining the top mass it is necessary to determine the neutrino momenta. The system is underconstrained but it can be solved by imposing the W and top masses in the event, once the lepton-jet assignment is chosen. In the pairing, jets which are b-tagged are favoured as candidates from the top decays. This is realised by two different methods, as described in [3], where the best hypothesis for the top mass is obtained by solving iteratively the equation for different values of a probe top mass. From the distribution of the best top mass hypotheses the value of  $m_t$  is then extracted by two template fits, as shown in figure 1. The signal is taken



Figure 1. Reconstructed top masses in the two different methods of reference [3], and best template fits superimposed.

from the MC predictions at different values of the top mass, and the backgrounds are partially taken from data (in the case of Z+jets background) and from MC (Single top, top-pair, W+jets and di-bosons). The methods, individually calibrated on MC, show a linear behaviour on the top mass and a residual small bias, which is corrected for. The two analyses provide compatible results and a statistical correlation, studied via pseudo-experiments, of 0.57. They are combined and yield a top mass of:

$$m_t = (175.5 \pm 4.6(stat) \pm 4.6(syst))GeV/c^2$$
 (1)

where the dominant systematic error is the knowledge of the jet energy scale, assessed in CMS to be in a range between 2 and 4%, as a function of the jet energy and rapidity [4].

#### 3. The top pair mass

Studying the top pair mass is particularly important as a measure in the frame of the SM, but also as a probe of the presence of new physics in the top sector. Several models [5] predict heavy s-channel resonances in top-pair production, that may give rise to resonant structures, or more generally a distortion in the shape of m(tt). The kinematics of top-pair production can be strongly influenced by the presence of new heavy particles. In particular, they may give rise to highly boosted top quarks, whose decay products may progressively merge, imposing new constraints in the way the events must be (triggered and) reconstructed. In what follows we present a full analysis optimized for the threshold of top-pair production, and studies for the reconstruction of highly boosted top pair quarks.

### 3.1. Top pair mass at the threshold of top pair production

This measurement is performed by exploiting semi-leptonic final states with the presence of an electron or a muon. Events are triggered by the presence of an isolated lepton, which is required to have a minimum transverse momentum of 20 GeV/c for muons and 30 GeV/c for electrons. A cut at 20 GeV on the minimum amount of missing transverse energy is required to substantially reduce the QCD component, and at least three(four) central jets are required with different thresholds in  $p_T$  of 70/50/30(/30) GeV/c. The selected events are divided in eight categories, four per lepton family, according to the number of jets and b-tags in the event. The four categories are composed by events with three jets with one b-tag, and four jets with either 0, 1 or 2 b-tags. The yields in data agree within errors with the predictions in all the eight categories, and sum up to 769 events seen in data with 822 expected. The expected number of events is inferred from MC with the exception of the QCD component, determined from control regions in data themselves.

The events can be reconstructed with a kinematic fit, where W and top masses are imposed. The main ambiguity in this process is the correct pairing of jets in forming the candidate top quarks. For this, a  $\chi^2$  method is used, choosing the pairing that gives the best similarity to a top-pair event for what concerns the leptonic and hadronic masses, the transverse momentum of the top-pair system, and the scalar sum of the transverse energy in the event. It has been verified that this procedure introduces no significant bias in the search of new physics in the top-pair production.

The improvement of the use of a kinematic fit is shown in figure 2, which illustrates



Figure 2. Expected resolution on the mass of the top mass pair before and after a kinematic fit, for the semileptonic muon channel and the electron one.

the reduction of the mass resolution when imploying a fit to the event. The improvement is significative up to invariant masses of about  $1.5 \text{ TeV/c}^2$ . For events with only three jets, no kinematic fit is applied.

The mass distributions seen in data agree well with the expectations in all the categories, as detailed in [6]. As an illustration, the distributions of the four jet bins with one and two b-tags in the muon channel are reported in figure 3 with the full 2010 statistics. The MC distributions have been normalized to the collected luminosity. Since no excess is found, the observed distributions in data are used to set limits on a new potential narrow resonance in top-pair production. The statistical approach for doing this is a fully Bayesian one, where the mass distributions are modelled by templates for the signal (a generic Z' narrow-width resonance with SM couplings to fermions) and the backgrounds (mostly for MC, except for QCD, taken from data sidebands). The templates are parametric in all uncertainties, which are included as nuisance parameters to be integrated out. The parametric dependence on nuisances in each



Figure 3. Top pair mass distributions for the muon channel in the four jets, one and two-b-tags categories.

bin is fitted via cubic functions, so that their impact in both rates and shapes can be taken into account. The most important nuisance parameters from systematic sources are background uncertainties, including theory ones like the  $Q^2$  dependence, jet energy scale and resolution uncertainties, b-tagging efficiency and luminosity.

An integration of the likelihood over nuisances is performed in order to derive upper limits on the production cross section of a narrow resonance. They are shown in figure 4, as a function



Figure 4. Expected and observed 95% upper limit on the production cross section of a generic Z'. The band includes statistical and systematic uncertainties.

of the resonance mass. The figure shows both the expected limit, and the one observed in data. Both are in agreement, with no visible excess in the entire mass range in the reach of this analysis. With only 36/pb of data, models predicting cross sections of about 10 pb for masses of about 1TeV can already be excluded.

#### 3.2. Boosted tops

As discussed, boosted top configurations may originate from the decay of a very massive object. In these circumstances leptons from W decays may progressively loose their isolation and the jets from the hadronic top deays overlap partially or totally, making it impossible to recur to standard reconstruction techniques.

In such final state topologies it becomes essential to be able to analyse jet substructures. The method investigated in CMS, called top tagging, uses a modified Cambridge-Aachen (C-A) algorithm, as described in [7] and in [8]. Jets are first clustered using the C-A algorithm, which does not use any  $k_T$  weighting in the pairing, with a large value of R (0.8). The found jets are decomposed by looking two steps back in the pairing history, searching for what we may call the "parents" and "grandparents" jets which have originated the final one. If the two parents have each at least 5% of the energy of the resulting jet, and at least the grandparents corresponding to one of the two parents have the same property, then the decomposition is declared successful. In these cases the jet is therefore decomposed in either three or four subjets. To be able to disentangle boosted top jets with respect to QCD, cuts on these substructures can be imposed. The two main variables that are used are  $m_{jet}$ , the mass of the original jet, and  $m_{min}$ , the minimum invariant mass of all the subjet pairs composing the jet. These variables are shown, for an hypothetical Z' signal into top-pair and for QCD events, as a function of the transverse momentum of the originary jet, in figure 5. As can be appreciated from the right hand side



**Figure 5.** Jet mass (upper row) and minimum di-jet mass of all jet pairs composing the original jet (lower row) as a function of the jet  $p_T$  for a Z' signal into top pairs (left column) and QCD events (right column).

plots in the figure, as the originary jet gets boosted, the more likely it is that it collectes all the decay products of the top quark. The merging of the W boson is also visible in the plots. No such structures are present for pure QCD jets. The cuts imposed on these variables are 100 GeV/c<sup>2</sup> <m<sub>jet</sub> <250 GeV/c<sup>2</sup> and m<sub>min</sub> >50 GeV/c<sup>2</sup>. We refer to this procedure as top tagging. The efficiency of top tagging is determined on Z' signal samples as a function of the boost of the originary jet. Efficiencies of about 40-50% for boosts between 600 GeV to 1 TeV are found, going down to about 30% for 2 TeV or more.



Figure 6. Predictions, for different models, of the jet mass and the minimum di-jet mass of all jet pairs composing the original jet for QCD events

Both  $m_{jet}$  and  $m_{min}$  are already pretty well described in pure SM QCD production by the current hadronisation models, as shown in figure 6. The dependence of the shape of the histograms on the different tunings is mild, increasing the robustness of the choice of these variables as good discriminators between boosted top signal and QCD background.

An essential ingredient for an analysis based on top tagging is to have precise knowledge of the QCD background. This can be determined in a simple way directly from the data by using di-jet events where one side is anti-top tagged and by parametrizing the tagging efficiency in the probe side as a function, for instance, of the jet transverse momentum. This is illustrated in figure 7 for 2010 data. The top mistag rate is shown as a function of the jet  $p_T$ . Once again, the level of agreement between what is observed from the data and what predicted by the various parton shower and hadronization models in the MC is remarkable.

#### 4. Conclusions

Studying top pair production at the LHC is fundamental for both constraining the SM and searching for hints of presence of new phisics at the TeV scale. Two important analyses in this respect involve the determination of the top mass and the reconstruction of the mass of the top-pair. Both tasks need an excellent understanding of jet production and pairing, and jet energy calibration. Techniques to improve in all aspects are already in place in both analyses. The searches for new physics signals in top-pair production will also entail new issues in jet reconstruction, namely the ability of resolving jet substructures. This is also being successfully addressed in CMS.

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Figure 7. Top mistag rate as determined from 2010 QCD data.

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