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Measurement of the top quark mass and the top-antitop invariant mass in pp collisions at 7 TeV with the CMS detector

Martijn MULDERS[*†]
CERN, Geneva
E-mail: martijn.mulders@cern.ch

We present measurements of the top quark mass in proton-proton collisions at the LHC at a centre-of-mass energy of 7 TeV using data collected by the CMS experiment during the years 2010 and 2011. Measurements are presented in all possible final states originating from top-pair production, and the different reconstruction methods to extract the top quark mass are discussed. Particular emphasis will be given to the contribution of systematic uncertainties. The results of the various channels are combined and compared to the world average. The determination of the top-pair invariant mass is also presented, and the result interpreted in the light of possible new physics signatures in the production of top-quark pairs.

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[*]Speaker.
[†]on behalf of the CMS Collaboration

PoS(EPS-HEP2011)355

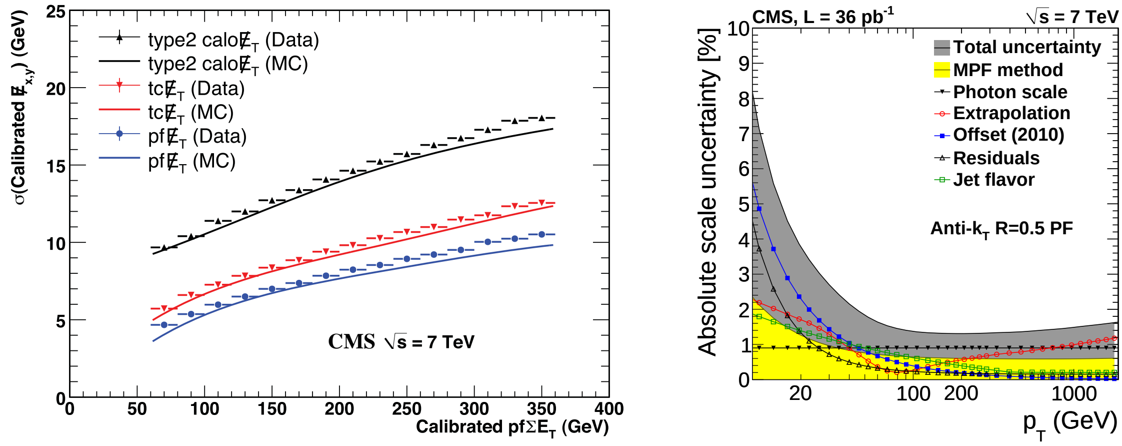

Figure 1: The resolution of the calibrated missing transverse energy versus the sum of the transverse energy in data and simulation for various algorithms [7] (left) and the various components of the jet calibration uncertainty as a function of jet transverse momentum using the Particle Flow algorithm [8] (right).

This report summarizes two measurements of the top quark mass [1, 2] and two analyses searching for signatures of new physics in the top-pair invariant mass distribution [3, 4]. The top mass measurement is performed using $t\bar{t}$ events in the fully leptonic [1] decay channel and the lepton+jets [2] channel, based on 36 pb^{-1} of data collected by the CMS experiment in pp collisions with a centre-of-mass energy of 7 TeV at the LHC in 2010. The $t\bar{t}$ invariant mass analyses were performed with 36 pb^{-1} of data in the lepton+jets channel [3], and 886 pb^{-1} of data collected in 2011 in the fully hadronic decay mode [4]. A more detailed description of the CMS detector can be found in [5].

1. Reconstruction of Jets and Missing Transverse Energy in CMS

For precise measurements in complex final states such as $t\bar{t}$ events, the accurate reconstruction of jets and the missing transverse energy (MET) is crucial. The analyses presented here all use the CMS Particle Flow (PF) algorithm [6], which uses information from all subdetectors aiming to reconstruct and identify all particles produced in the collision. The particles are reconstructed in mutually exclusive categories: charged hadrons, photons, neutral hadrons, muons and electrons. These PF particles are then used as input to an anti-k_T jet clustering algorithm with distance parameter R=0.5 to form jets, and the missing transverse energy (MET) is simply defined as the component of the vectorial sum of the momenta of all reconstructed PF particles in the event, transverse to the LHC beam direction.

As shown in Fig. 1(left), the combined use of tracking and calorimetry in the PF algorithm leads to a large improvement in the relative MET resolution compared to calorimeter-only reconstruction of MET [7]. Similarly, the use of PF reconstruction was found to improve the jet resolution, and generally reduce the dependence of the jet response on physics properties of the jet such as differences induced by a different jet flavour. Using the full set of 2010 data, CMS has achieved an excellent understanding of the jet energy resolution and calibration [8], leading to an overall jet

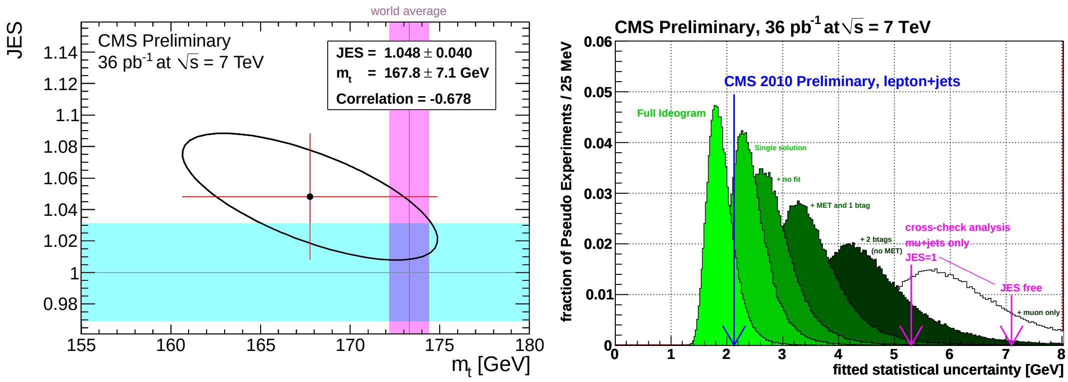

Figure 2: The 68% level confidence region in the m_t – JES plane from the Template analysis (left), and an illustration of the expected improvement in statistical precision for the measurement of the top quark mass, obtained by the Ideogram analysis (right) [2].

energy scale uncertainty of 2% or less at a jet p_T of 40 GeV or more as illustrated in Fig. 1(right). Such a remarkable understanding of the jet calibration provides a solid basis for the measurements of the top quark mass described in the following.

2. Measurement of the top quark mass in the di-lepton channel

In this decay channel events passing a single lepton trigger are selected by requiring at least two jets with a p_T above 30 GeV and two isolated leptons of opposite charge, considering the combinations ee, $e\mu$ and $\mu\mu$. In addition, the MET is required to be larger than 30 GeV (ee, $\mu\mu$) or 20 GeV ($e\mu$). To choose the 2 jets that are assumed to be the b-jets from the top quark decays, priority is given to jets that are b-tagged, followed by maximum jet p_T. To solve the underconstrained system two methods are used, the KINb and AMWT method [1]. The two analyses are combined and calibrated using Monte Carlo pseudo-experiments. Systematic uncertainties were evaluated and are dominated by the uncertainty in jet energy scale calibration. The resulting top mass measurement,

$$m_t = 175.5 \pm 4.6(\mathrm{stat}) \pm 4.6(\mathrm{syst}) \ \ \mathrm{GeV},$$

was the first top mass measurement performed *not* at the Tevatron [1]. A more detailed breakdown of the components of the measurement uncertainties is given in Table 1(first column).

3. Measurement of the top quark mass in the lepton+jets channel and combination

In the lepton+jets channel, events are selected with at least 4 PF jets with $p_T > 30$ GeV and pseudo-rapidity $|\eta| <2.4$, and one isolated electron ($p_T >30$ GeV, $|\eta| <2.5$) or muon ($p_T >20$ GeV, $|\eta| <2.1$). Two analyses are performed. In the first analysis, two jets are required to be b-tagged with a secondary vertex tagger, leading to a $t\bar{t}$ selection of high purity. A template fitting technique is used to extract both an overall scale factor for the jet energy calibration, and the top mass [2]. The result of this two-parameter fit is shown in Fig. 2(left). It is compatible with a JES scale factor equal to one, and with the top mass measured at the Tevatron [2].

Table 1: The measured m_t and its uncertainties for the two measurements and the combination in GeV.

	Dileptons	Lepton+jets	Correlation factor	Combination
Measured m_t	175.5	173.1		173.4
Statistical Uncertainty	4.6	2.1	0	1.9
Breakdown of Systematic Uncertainty:				
Jet energy scale (correlated part)	2.25	2.25	1	2.3
Jet energy scale (uncorrelated part)	3.28	n/a	0	0.4
Jet energy resolution	0.5	0.1	1	0.1
Lepton energy scale	0.3	n/a	0	0.0
Missing p_T scale	0.1	0.4	1	0.4
Pile-up	1.0	0.1	1	0.2
b-tagging	0.4	0.1	1	0.1
Background	0.1	0.5	0	0.4
Parton density function	0.5	0.1	1	0.2
MC generator	0.4	n/a	0	0.0
Underlying event	1.4	0.2	1	0.3
ISR/FSR	0.2	0.2	1	0.2
Jet-parton scale	0.7	0.4	1	0.4
Factorization scale	0.6	1.1	1	1.0
Fit calibration and MC statistics	0.3	0.1	0	0.1
Total Systematic Uncertainty	4.6	2.7		2.7
Combination weight	12%	88%		

The second analysis uses a different approach, leading to a substantial improvement in measurement precision for the 36 pb^{-1} of data analyzed. This improvement is illustrated step-by-step in Fig. 2(right), where the distributions show the expected statistical uncertainty from MC pseudo-experiments. The following improvements were implemented: the JES is not fitted *in*-situ but taken from the general CMS jet calibration (ie JES=1) [8]; events with 0, 1 or more b-tagged jets are all used; a constrained kinematic fit is applied to improve the mass resolution; and for each event all possible jet-to-parton assignments are included in an event-by-event likelihood using the Ideogram technique [2]. This analysis has a significantly improved expected experimental precision, and is used as reference analysis for this measurement, giving the following result: $m_t = 173.1 \pm 2.1(\text{stat}) \pm 2.7(\text{syst})$ GeV. Systematic uncertainties are listed in Table 1(2$^{\text{nd}}$ column). The table also shows the estimated correlations between the measurements in the lepton+jets and the dilepton channel, for each of the sources of uncertainty. Taking these correlations into account, a combination of the two measurements was performed, leading to the combined result of

$$m_t = 173.4 \pm 1.9(\text{stat}) \pm 2.7(\text{syst}) \text{ GeV},$$

corresponding to a relative precision of better than 2% on the top quark mass, achieved with just

PoS(EPS-HEP2011)355

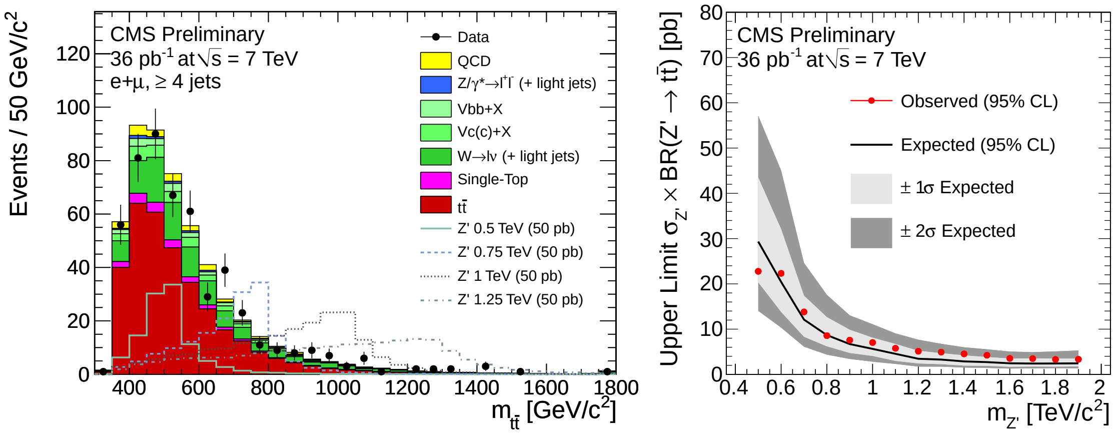

Figure 3: Reconstructed $t\bar{t}$ invariant mass in the category with at least four jets in the combined lepton+jets channel (left) and upper limit for narrow *Z'* production obtained (right) [3].

36 pb^{-1} of CMS data.

4. Measurement of the top-antitop invariant mass in the search for new physics

Several scenarios for physics beyond the Standard Model (BSM) feature new gauge interactions with favourable couplings with the third-generation quarks. Such couplings would result in new heavy states, referred to generically as *Z'*, which could show up as resonances in top pair production at the LHC, altering the shape of the $t\bar{t}$ invariant mass distribution.

In the lepton+jets channel, a selection very similar to the one described in the previous section was used to search for resonances in the $t\bar{t}$ invariant mass spectrum. An overall fit was performed for separate subsamples with different jet and *b*-tag multiplicity. An example for one subsample is shown in Fig. 3(left). No significant deviations with respect to the Standard Model prediction were found, and a limit on the cross-section times branching ratio (BR) of a hypothetical narrow *Z'* resonance is obtained, as shown in Fig. 3(left).

In the fully hadronic final state, a dedicated analysis was performed to search for (BSM) signatures in the high-invariant-mass region. At such high mass, the top quarks are produced with sufficiently high boost that it is not unlikely that two or three jets from the top decay merge in one fat jet. New techniques were developed to look for substructure in fat jets, and events were selected where on opposite side of the event merged top-candidates were found, looking for the sign of a *W* in merged jets [4]. In Fig. 4(left) the invariant mass is shown of pairs of sub-jets in fat jets, clearly showing evidence of a peak approximately at the *W* boson mass, and showing good agreement between data and the prediction for MC simulation. Analysis of 886 pb^{-1} of CMS data recorded in 2011, did not reveal a deviation from the standard model prediction, and a sub-picobarn upper limit on the cross-section times branching ratio for a *Z'* resonance was established for a resonance mass above 1.1 TeV, as shown in Fig. 4(right). This excludes at 95% CL the Kaluza-Klein gluon model with a mass between 1.0 and 1.5 TeV.

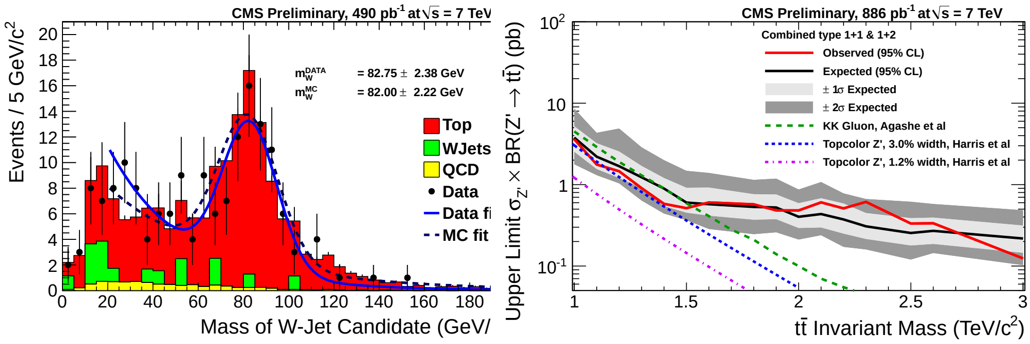

Figure 4: Evidence of W decays inside the highest-mass jet in semileptonic events in a control sample (left) and the limit on Z' production obtained in the fully hadronic channel search (right) [4].

5. Summary

Using 36 pb^{-1} of CMS data from pp collisions at 7 TeV the top quark mass was measured in the dilepton and lepton+jets channels with a combined relative precision of better than 2%. With up to 886 pb^{-1} of data, the $t\bar{t}$ invariant mass spectrum was investigated in the lepton+jets and fully hadronic channel, using novel top tagging techniques that identify boosted top candidates in which decay products are merged inside jets. A good agreement with standard model predictions was observed, yielding upper limits on BSM signatures in the production of $t\bar{t}$ pairs.

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