

# Measurement of Missing Transverse Energy in Top Pair Events

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**Abstract.** A differential cross section measurement of top quark pair production with missing transverse energy is presented using  $5.1 \text{ fb}^{-1}$  of data collected using the CMS detector at the LHC at a centre of mass energy of 7 TeV. The analysis selects events with a single isolated high energy electron or muon, which is assumed to come from one of the W bosons produced in the decays of the top quark and antiquark. The differential cross section is measured in bins of missing transverse energy. The results are consistent with the predictions of simulation.

## 1. Introduction

During 2011 the LHC produced almost 800000 top quark pairs and is therefore often referred to as a top quark factory. This allows a detailed investigation of the missing transverse energy ( $E_T^{\text{miss}}$ ) in top quark pair events. This can potentially be used not only to verify the current models of top quark production, but also to measure rare Standard Model (SM) processes with additional  $E_T^{\text{miss}}$ . Top pair production is a major background for new physics searches involving missing transverse energy signatures, so it is important that the distribution of  $E_T^{\text{miss}}$  in top events is well understood. In addition there are many new physics scenarios that produce additional  $E_T^{\text{miss}}$  in association with a  $t\bar{t}$  pair.

Top quarks decay with close to 100% probability into a W boson and a bottom quark. In  $t\bar{t}$  pair production the semileptonic channel involves one of the W bosons decaying into a lepton along with its associated neutrino while the other W boson decays hadronically.

New results from the CMS experiment at the LHC are presented, based on data collected at a centre-of-mass energy of 7 TeV during 2011, measuring the distribution of  $E_T^{\text{miss}}$  in the production of top quark pairs and comparing with the predictions from event generator codes. The CMS detector is described in detail elsewhere [1].

## 2. Analysis Strategy

The analysis is designed to select semileptonic top pair decays, those in which one of the W bosons has decayed leptonically and the other has decayed into a quark pair. We include decays to electrons or muons, plus an accompanying neutrino. Additional leptons are vetoed to avoid contamination from dilepton processes. W boson decays to  $\tau$  leptons are not explicitly searched for in the analysis although the selected samples include events where the  $\tau$  decays to muons and electrons. The final state includes the charged lepton and neutrino, and four jets of hadrons from the decays of the top quarks. Two of these come directly from the decays of top to bW, and



contain b-flavoured hadrons; the other two jets come from the decay of a W. The requirement of two b tagged jets enables the number of background events selected to be minimised. A sizeable fraction of events in simulation contain extra jets due to hard QCD radiation.

In semileptonic top pair decays an imbalance is expected in the measured momentum, in the plane perpendicular to the beam direction, due to the presence of a neutrino in the final state. Subsamples are divided according to the measured missing transverse momentum, and study the distribution of the polar angle of leptons to the beam axis in each subsample. As a consequence of the large mass of the top quark, the leptons in top pair events are produced predominantly at large angles to the beam axis, whereas the main background processes give rise to leptons produced at smaller angles. A template fit of the lepton pseudorapidity is used to estimate the composition of each subsample, and hence the number of top pair events in the range of missing transverse energy concerned.

The analysis is initially carried out separately for event samples where the charged lepton is a muon or an electron. The final result is based on a combination of the two channels, and is compared against predictions from a range of Monte Carlo event generator codes.

### 3. Simulation

For the simulation of the  $t\bar{t}$  signal sample the MADGRAPH event generator [2] is used, which implements the relevant matrix elements up to three additional partons. The generated events are subsequently processed with PYTHIA [3] for parton showering and hadronisation. The PYTHIA parton shower is matched to the jets from the hard QCD matrix element via the MLM prescription [4] with a threshold of 40 GeV.

All of the samples are generated at the centre of mass energy of 7 TeV, using the CTEQ6L parton distribution functions [5]. PYTHIA is used for the radiation and fragmentation using the prescriptions in [6] and the underlying event tuning described in reference [7].

For comparison with the measured lepton  $|\eta|$  and  $E_T^{\text{miss}}$  distributions (Figure 1), the events in the simulated samples are normalised to the integrated luminosity of the data sample,  $5.05 \text{ fb}^{-1}$ . For the SM top-quark pair production cross section, the next-to-next-to-leading (NNLO) order value [8] of 163 pb is used. For the vector boson production, the inclusive NNLO calculation from [9] is used.

The Monte Carlo samples used are reweighted to match the pileup conditions of the data. A further reweighting takes account of known small differences between the performance of the b-tagging algorithm on data and Monte Carlo.

### 4. Cross Section Measurement

#### 4.1. Fit Procedure

The observed events are divided into five  $E_T^{\text{miss}}$  bins. In each bin, a template fit of the observed distribution of lepton rapidity  $|\eta_\ell|$  is used to subtract the main backgrounds and estimate the number of  $t\bar{t}$  events.

Three separate  $|\eta_\ell|$  distributions are produced for each  $E_T^{\text{miss}}$  bin as input to the template fit. The first template is the  $|\eta_\ell|$  shape for top-like events, including  $t\bar{t}$  and single top. This is taken from simulation, where the relevant event samples all give similar shapes. The  $|\eta_\ell|$  distributions for the W+jets and Z+jets samples are summed together to give the second template. The distribution for QCD multijet events is estimated from data, looking at control samples where one of the lepton selection cuts is inverted.

A binned maximum likelihood fit is then used to estimate the contribution of each template to the overall  $|\eta_\ell|$  distribution seen in data. The fit yields an estimate of the number of top-like events observed in the  $E_T^{\text{miss}}$  bin. By subtracting the Monte Carlo estimate for the contribution from single-top production, the number of  $t\bar{t}$  events is obtained.

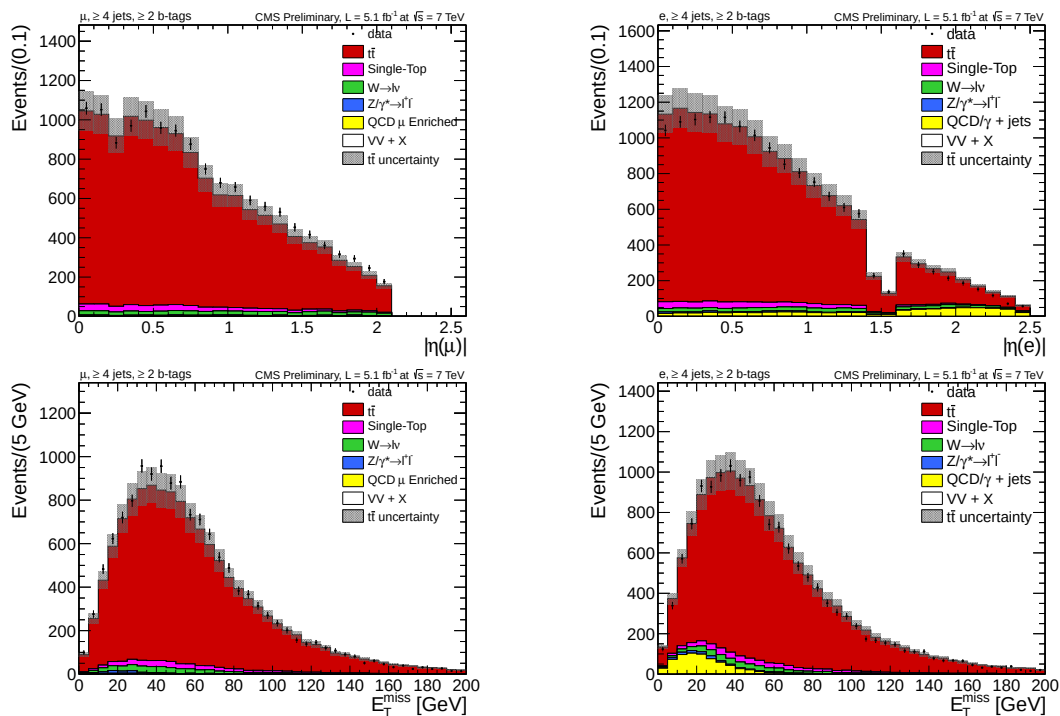


**Figure 1.** Kinematic variable distributions seen in the event samples after all cuts. Points with error bars are the 2011 data, stacked histograms the Monte Carlo expectations, the grey error bars the uncertainty on the measured  $t\bar{t}$  cross section. Left plots: muon+jets; right plots: electron+jets. Top: lepton  $|\eta_\ell|$ ; Bottom:  $E_T^{\text{miss}}$ .

#### 4.2. Cross Section Corrections

The differential cross section for semileptonic  $t\bar{t}$  production is measured as a function of  $E_T^{\text{miss}}$ , correcting for the effect of  $E_T^{\text{miss}}$  bin migration due to finite detector resolution; the experimental acceptance and selection efficiency; and the contribution of other  $t\bar{t}$  decay channels. The required correction factors are derived from simulation.

### 5. Systematic Errors

The uncertainties are estimated by varying the input quantities according to their theoretical and/or experimental uncertainties and observing the change in the final result. The propagated uncertainties are set to be symmetric, conservatively taking the larger of the upward and downward variation. Correlations between input variables are taken into account.

The dominant sources of systematic error are the uncertainty in the measurement of  $E_T^{\text{miss}}$ , and the theoretical uncertainty in the W-plus-jets background sample. Other non-negligible sources of uncertainty are the energy and momentum scales for electrons, muons and jets. The error in the QCD estimation is relatively large, but this is mitigated by the small QCD contamination of the sample after requiring two b-tagged jets. Uncertainties that affect the overall rate (e.g. the luminosity error) contribute a negligible amount as they cancel in the normalisation.

### 6. Results

The procedure described in section 4 has been carried out for both muon and electron samples, to give measurements of  $\frac{d\sigma_{t\bar{t}}}{dE_T^{\text{miss}}}$  in five bins of  $E_T^{\text{miss}}$ . The total  $\sigma_{t\bar{t}}$  measured with the same

analysis is used to arrive at a normalised differential cross section for each channel.

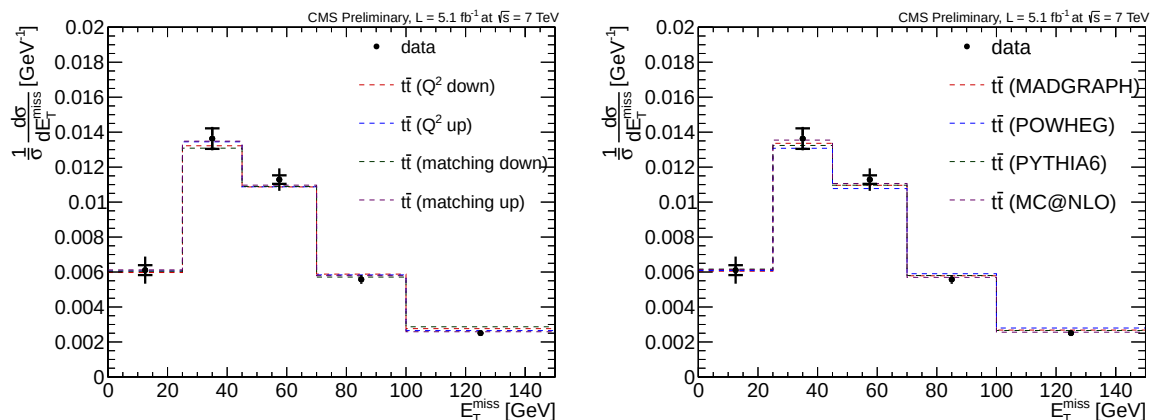


**Figure 2.** Comparison of normalised differential cross section result to matching threshold and  $Q^2$  scale up and down samples (left) and different generators (right) for the combination of both channels. The inner error bars indicate the fit uncertainty and the outer error bars the combined fit and systematic uncertainty.

The two channels have also been combined by summing the two cross section measurements in each  $E_T^{\text{miss}}$  bin, after all corrections. The summed total cross section is then used to normalise the results. A comparison to other generators and different theory inputs is shown in figure 2.

## 7. Summary

A measurement of the differential cross section of top quark pair production with respect to  $E_T^{\text{miss}}$  has been performed in pp collisions at a 7 TeV centre of mass energy, in  $5.1 \text{ fb}^{-1}$  of data collected by the CMS experiment at the LHC in 2011. The analysis selects events with a single isolated high energy electron or muon, which is assumed to come from one of the W bosons produced in the decays of the top quark and antiquark. The differential cross section is measured in five bins of missing transverse energy. The results are consistent with the predictions of Monte Carlo generators.

## References

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