

Measurement of Differential $t\bar{t}$ Cross Sections at 7 TeV

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Abstract. A measurement is presented of the normalized differential cross sections of top-quark pair production in pp collisions at a center of mass energy of 7 TeV, using 1.1 fb^{-1} of data collected in 2011 by the CMS experiment. The measurement is performed using five different final states with one or two muons or electrons in the final state. The event selections yield high purity $t\bar{t}$ samples. Kinematic reconstructions are performed to obtain full information of the top quarks, the $t\bar{t}$ system and the final state leptons. The results are compared to several QCD predictions up to next-to-leading order.

1. Introduction

The production cross section of top-quark pairs ($t\bar{t}$) is measured as a function of several top quark related quantities, utilizing final states with leptons (ee , $\mu\mu$, $e\mu$, $e+\text{jets}$, $\mu+\text{jets}$). Such measurements are a precision test of perturbative quantum chromodynamics (pQCD) and an important check for searches beyond the standard model (SM) where $t\bar{t}$ is a major background. Furthermore, they are sensitive to phenomena beyond the SM such as the production of a massive Z-like vector boson that could manifest itself as a resonance in the $t\bar{t}$ mass spectrum. This measurement is performed using 1.1 fb^{-1} data recorded by the CMS experiment [1] in 2011. All details are discussed in Ref. [2].

2. Event Selection and Background Estimation

The event selection is optimized to obtain a high-purity $t\bar{t}$ sample. To identify events of interest, single lepton or dilepton triggers are required for the corresponding decay channel.

Exploiting the event topology, events are required to contain isolated leptons in the final state. Two opposite sign leptons ($p_T > 20 \text{ GeV}$, $|\eta| < 2.4$) are required in the dileptonic channels and exactly one lepton ($p_T > 30 \text{ GeV}$, $|\eta| < 2.1$) in the $e/\mu+\text{jets}$ channels. Events with additional loosely isolated leptons are vetoed for the $e/\mu+\text{jets}$ channels while events with invariant dilepton masses smaller than 12 GeV are vetoed for the dileptonic channels to suppress QCD multijet background.

Furthermore, the events are required to contain at least two jets for the dileptonic channels and at least four jets for the $e/\mu+\text{jets}$ channels. Jets are clustered from particles reconstructed by a particle flow algorithm [3] using the anti- k_t algorithm with $R=0.5$ [4] and are selected if they have a transverse momentum $p_T > 30 \text{ GeV}$ and pseudo-rapidity $|\eta| < 2.4$. Additionally, at least one jet in the dilepton channels and at least two jets in the $e/\mu+\text{jets}$ channels are required to originate from bottom quarks. To identify them, an algorithm based on the reconstruction of



secondary vertices is used [5].

To further reduce background stemming from Drell-Yan processes, events in the ee and $\mu\mu$ channels are required to contain a minimal missing transverse energy of 30 GeV and the invariant mass of the two leptons is required to be outside a ± 15 GeV window around the Z-boson mass. For the $e\mu$ and e/μ +jets channels, the selected samples are expected to contain at least 90% $t\bar{t}$ events and events with single top quarks are the largest background.

In the ee and $\mu\mu$ channels, the fraction of $t\bar{t}$ events is expected to be above 80%. Leptonically decaying Z bosons accompanied by additional jets in the final state constitute the main background and are estimated from data by extrapolating the measured number of events within the veto region around the Z-boson mass into the signal region.

3. Kinematic Event Reconstruction

In order to fully reconstruct the event topology, the final-state objects (jets, leptons, and neutrinos) have to be correctly associated to their parent top quark. The measured missing transverse energy is assumed to reflect the transverse component of the neutrino momentum. Kinematic constraints, e.g. the reconstructed W-boson masses and equal reconstructed top-quark masses, are used in order to compensate for the unmeasured z component of the neutrino momentum and to build an event hypothesis.

In the e/μ +jets channels a kinematic fit is performed by varying the four-momenta of the final state objects to fulfill the constraints [6]. The five leading jets are considered to construct a hypothesis, using the b-tag information to assign jets as b jets from the $t \rightarrow bW$ decay. In case of several hypotheses, the one with the lowest variation concerning the object resolution (minimum χ^2) is chosen.

Due to the underconstrained system in the dileptonic final state with two neutrinos, additional constraints are needed [7]. A set of hypotheses is created by fixing the top-quark mass and performing a scan from 100 to 300 GeV in 1 GeV steps. Hypotheses containing b-tagged jets are preferred. Finally, the hypothesis with the most probable reconstructed neutrino energy in comparison to a reference spectrum from simulation is chosen.

4. Normalized Differential Cross Sections

In order to quantify migration effects, the two quantities purity (p) and stability (s) are used. Purity (stability) is the number of particles generated and correctly reconstructed in a certain bin i divided by the total number of reconstructed (generated) particles in the same bin:

$$p = \frac{N_{\text{gen\&rec}}^i}{N_{\text{rec}}^i} ; \quad s = \frac{N_{\text{gen\&rec}}^i}{N_{\text{gen}}^i}$$

A value of one corresponds to no migration. For each variable and decay channel, the binning is optimized independently to limit the migration effects to a reasonable level (s and p > 0.4–0.5). For the kinematic quantities of the final state leptons, migration effects are typically less pronounced (s and p > 0.9).

The differential cross sections are derived for every bin i from the number of measured events in data (N_{data}^i) by subtracting the background (N_{BG}^i) and dividing by the binwidth (Δ^i), the integrated luminosity (L), the efficiency (ϵ^i), and the in situ measured inclusive cross section in the same phase space σ_{PS} :

$$\frac{1}{\sigma} \frac{d\sigma^i}{dX} = \frac{1}{\sigma_{\text{PS}}} \frac{N_{\text{data}}^i - N_{\text{BG}}^i}{\Delta^i \epsilon^i L}$$

The measurement is performed in the visible parton level phase space. Therefore, the efficiency, which includes migration corrections, is defined concerning events that contain leptons and quarks within the same kinematic region (p_{T} and $|\eta|$) as used for the event selection. This

avoids extrapolation into an unmeasured region of the phase space.

Dividing by the inclusive cross section normalizes the differential distributions to unit area and helps to reduce systematic uncertainties.

5. Systematic Uncertainties

Systematic uncertainties are evaluated separately for each source and measured distribution. Even with the 1.1 fb^{-1} subset of data recorded in 2011, the measurement is already limited by systematic effects. Due to the normalization concerning the inclusive cross section in the same phase space, all bin-by-bin correlated uncertainties cancel (at least partly). The remaining uncertainties are therefore shape uncertainties. The main model uncertainties originate from the matching threshold between matrix element calculation and parton showering and the renormalization and factorization scale Q^2 of the process. The main sources of experimental uncertainties are the jet energy scale and the b-tag efficiency.

6. Results

The $t\bar{t}$ production cross section is measured differentially as a function of the final state leptons (p_T , η), the top quarks (p_T , rapidity y) and the $t\bar{t}$ system (p_T , y , invariant mass) in all final states involving muons and electrons. For the dileptonic final states, the production cross section is additionally measured as a function of the lepton pair p_T and invariant mass. The measured points from data are compared to different SM simulations (MADGRAPH+PYTHIA, POWHEG+PYTHIA, MC@NLO+HERWIG) [8, 9, 10, 11]. Horizontal bin center corrections [12] (based on the simulation of MADGRAPH) have been applied to the data points in order to compare them to the continuous predictions from simulation. A selection of results can be found in Figure 1. In general, the different channels agree well with each other and the studied SM predictions. However, the transverse momentum of the top quarks (Figure 1 e, f) tend to be lower in data than predicted by the simulations. For the measurements as a function of the dilepton system (Figure 1 c, d), data prefers simulations including spin correlation (MC@NLO and POWHEG) over the one without (MADGRAPH). In particular, this is interesting as the invariant mass of two leptons is an important variable for searches.

7. Summary

This measurement is the most detailed differential cross section measurement at the LHC with $\sqrt{s}=7$ TeV so far, involving five different final states and nine measured quantities. Within the precision of this measurement, no significant deviation from the SM is observed. However, for the transverse momentum of the top quarks, data prefers a softer spectrum than predicted by the simulations (involving QCD predictions up to NLO).

References

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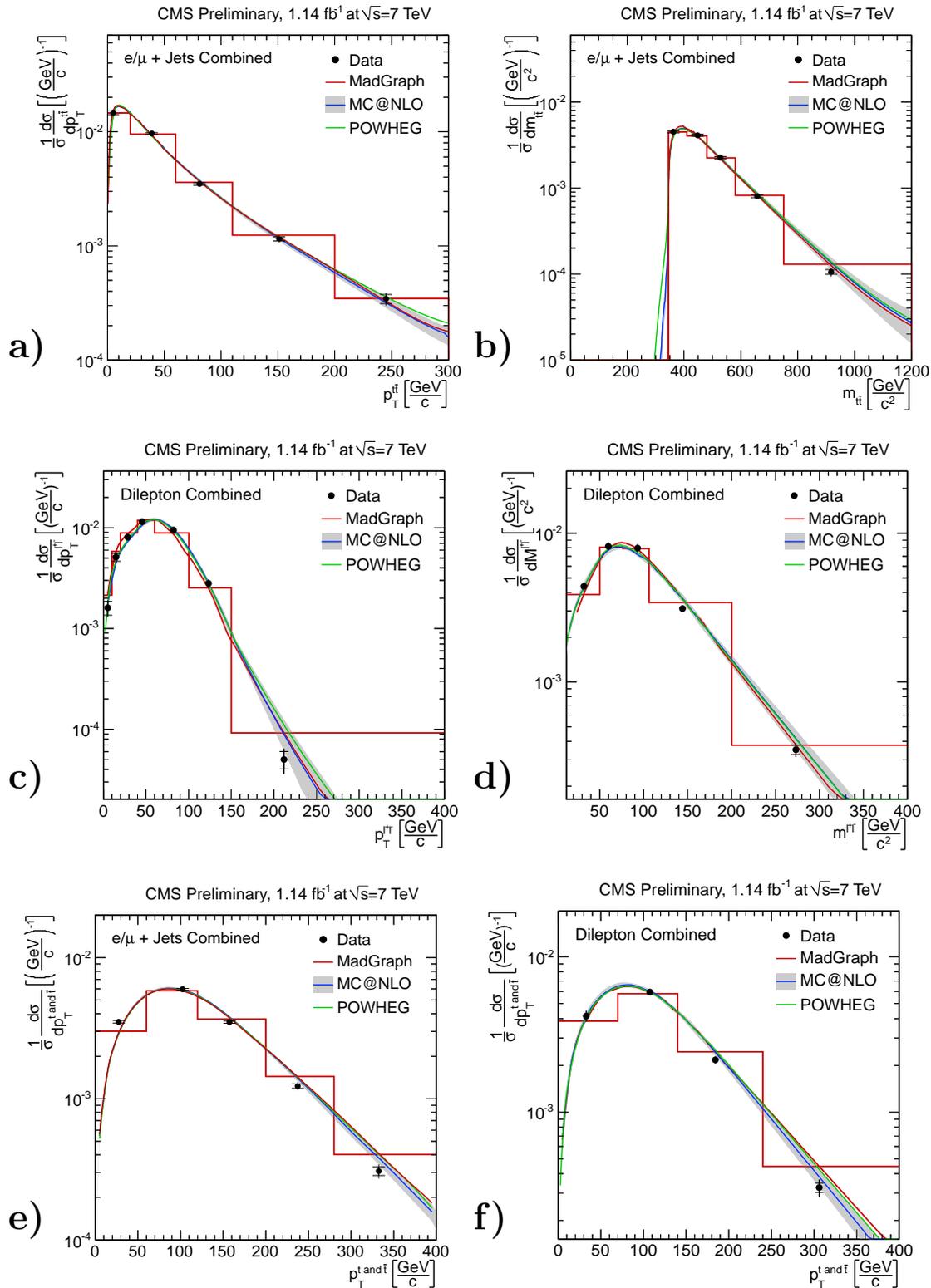


Figure 1. Normalized differential cross sections as a function of the transverse momentum (a) and invariant mass (b) of the $t\bar{t}$ system, the transverse momentum (c) and the invariant mass (d) of the lepton pair, and the top quark transverse momentum (e, f). Horizontal bin center corrections (using the MADGRAPH simulation) have been applied to the data points.