PROCEEDINGS OF SCIENCE

Top quark pair production cross sections at CMS

Juan R. González Fernández* **on behalf of the CMS Collaboration**
Universidad de Oviedo
E-mail: jrgonzal@cern.ch

A summary of the latest results on inclusive and differential $t\bar{t}$ cross sections by CMS is presented. Several new differential cross section measurements have been performed by CMS using an amount of 35.9 fb^{-1} of data collected in 2016. The studies include differential cross section measurements as a function of the $t\bar{t}$ system, the top quarks, its decay products and global event variables. Double-differential cross sections are also explored. Investigations on the jet substructure in $t\bar{t}$ events are also presented. Finally, the first measurement of the underlying event in $t\bar{t}$ events is summarized. All these new measurements provide excellent information about the agreement between the observations and different generators and theoretical parametrizations used in $t\bar{t}$ modeling.

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*Speaker.

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PoS(LHCP2018)240

1. Introduction

The top quark is the only quark that hadronizes before decaying. This property makes the top quark a unique particle to study very precisley several quantum chromodynamics (QCD) predictions, such as proton parton distribution functions (PDF). Furthermore, the top quark is also the most massive particle in the Standard Model (SM), with the strongest Yukawa coupling to the Higgs boson and a great potential to be related with new physics.

In the CERN Large Hadron Collider top quarks are mostly produced in pairs ($t\bar{t}$). The inclusive $t\bar{t}$ production cross section has been measured by CMS [1] at different centre-of-mass energies and collision systems (pp, pN). These measurements are in agreement with the SM predictions and, in some cases, the precision on the measurement overcomes the theory uncertainties.

Several differential $t\bar{t}$ cross sections have been measured in pp collisions as a function of different variables, including observables related to the jet substructure and the underlying event.

The general strategy followed in differential cross section measurements is based on using distributions at particle and parton level [2–4] and unfold the data so the observations can be directly compared with several simulation models. The particle-level results are presented in the fiducial region, so extrapolation uncertainties can be avoided, whereas parton-level measurements include the extrapolation to the full phase space based on next-to-leading-order (NLO) matrix element (ME) and simulation of parton shower (PS).

2. Inclusive cross sections

Latest measurements of the inclusive top quark pair production cross section in pp collisions by CMS have been performed at $\sqrt{s} = 13$ TeV in the dilepton [5] and lepton+jets [6] channels. Also, a recent measurement at $\sqrt{s} = 5.02$ TeV in pp collisions has been performed by CMS, showing a good agreement with the predictions and proving the reach of this measurement to constrain high-x gluon PDF [7].

A summary of inclusive $t\bar{t}$ productions cross section measurements by CMS in a wide range of centre-of-mass energies can be found in Fig. 1.

The first measurement of inclusive $t\bar{t}$ cross section in proton-lead collisions has been recently published by CMS [8]. This result uses a dataset with 174 nb^{-1} collected by CMS in 2016 at a centre-of-mass energy of $\sqrt{s[NN]}$ = 8.16 TeV.

This measurement was done selecting events containing one lepton and at least 4 jets and classifying the events according to the b-tag multiplicity. The distribution of the reconstructed mass of the hadronically decaying W boson is fitted to extract the signal. The measured cross section is 45 ± 8 nb, in agreement with the best QCD prediction.

3. Differential cross sections

Differential cross sections using the full 2016 dataset recorded by CMS, corresponding to a total luminosity of 35.9 fb^{-1}, where measured in the lepton+jets [2, 3] and dilepton [4] channels.

The nominal $t\bar{t}$ sample is simulated with Powheg v2 [9] and interfaced with Pythia v8.205 [10]. The underlying event is tuned using the CUETP8M2T4 derived from the full dataset at $\sqrt{s} = 8$ TeV [11].

PoS(LHCP2018)240

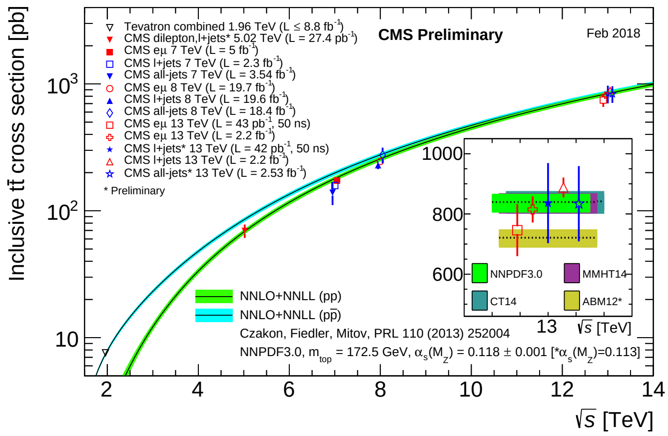

Figure 1: $t\bar{t}$ inclusive cross sections by CMS as a function of the centre-of-mass energies. [12]

The $t\bar{t}$ cross section as a function of different variables that not require the $t\bar{t}$ system to be reconstructed [2], such as the jet multiplicity, missing transverse momentum (p_T^{miss}), lepton p_T and η, transverse momentum of the leptonically decaying W boson (p_T^W), scalar sum of the jet p_T (H_T), and the scalar sum of the p_T of all the particles (S_T). The unfolded data are compared with several simulations. Uncertainties coming from several experimental sources and $t\bar{t}$ modeling are taken into account. The larges uncertainties come from the tW background estimate, the jet energy scale and the $t\bar{t}$ modeling.

Fig. 2 shows the differential cross section as a function of the jet multiplicity and the lepton p_T. A good agreement between data and simulation is observed for the Powheg+Pythia8 simulation with the CUETP8M2T4 tune for the jet multiplicity differential cross section, while a slope is observed in the case of the cross section as a function of the lepton p_T.

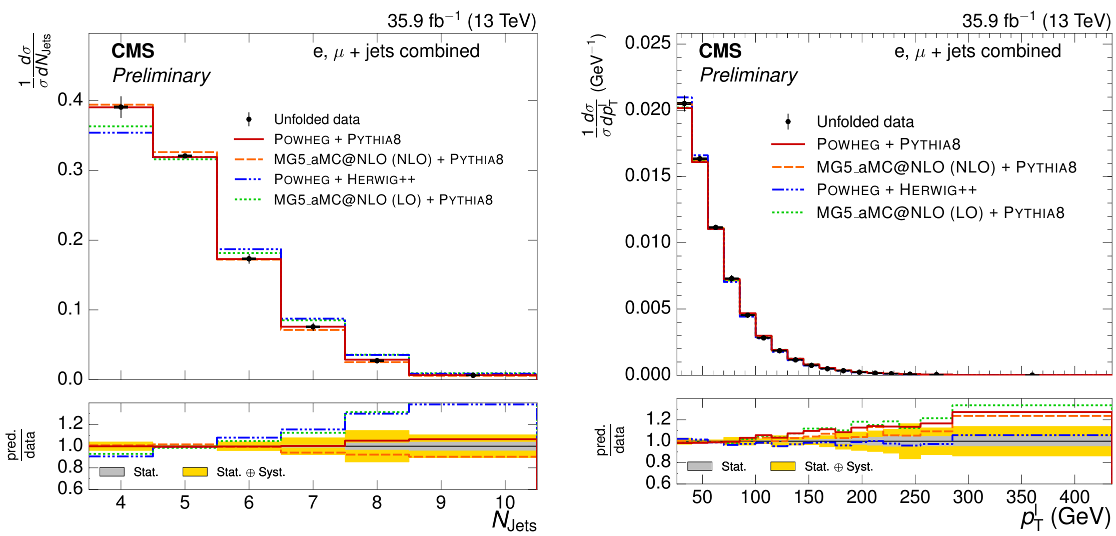

Figure 2: Differential $t\bar{t}$ cross section as a function of the jet multiplicity (left) and lepton p_T (right) and comparison with different simulations. [2]

The Powheg+Pythia simulation is found to be consistent with the observed data for most of the distributions, with some exceptions but always within the theoretical uncertainties.

Differential cross sections (and double-differential cross sections) have been also measured after reconstructing the $t\bar{t}$ system as a function of different variables related to the top quarks and the $t\bar{t}$ system [3].

In Fig. 3 the normalized differential $t\bar{t}$ cross section as a function of the leptonic and hadronic reconstructed top quark p_T is shown. A small slope is visible in the theory-to-data ratio for different models, including the nominal Powheg+Pythia model. Other differential cross sections presented in this study are mostly in agreement with the nominal model.

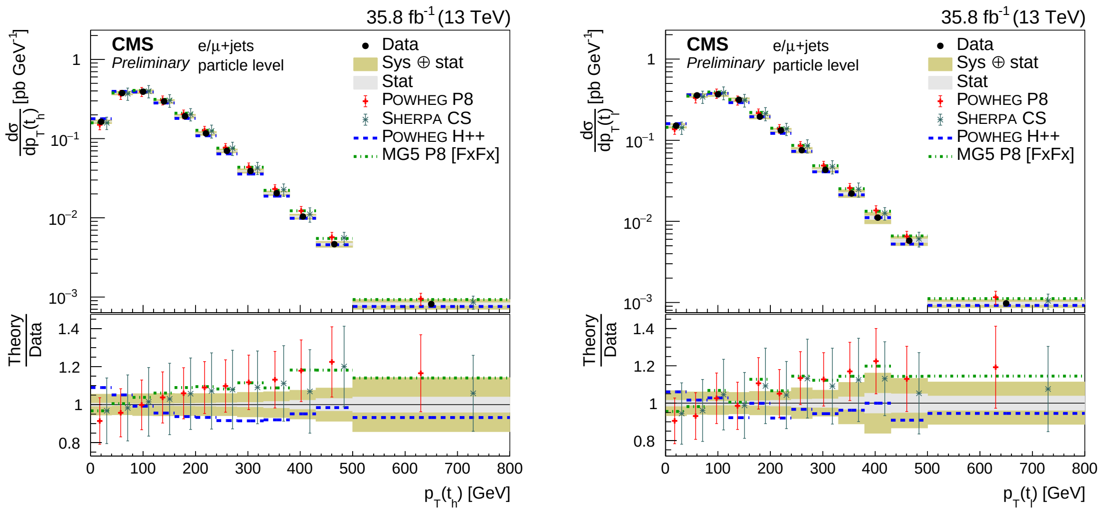

Figure 3: Normalized differential $t\bar{t}$ cross section as a function of the hadronic (left) and leptonic (right) top quark p_T and comparison with different simulations. [3]

In general, the Powheg+Pythia simulation describes well most of the studied distributions. The largest deviation is found in the softer top quark p_T spectrum predicted by this simulation.

Differential $t\bar{t}$ cross section measurements have been also performed in the dilepton channel [4]. Several distributios at unfolded to parton and particle level and the differential cross section are presented as a function of different variables related to the top quark, the $t\bar{t}$ system of their decay products.

As shown in Fig. 4, the top quark p_T is not well modeled by the nominal Powheg+Pythia simulation and a similar mismodeling is seen in the lepton p_T distribution.

Most of the measured differential cross sections are in agreement with the Powheg+Pythia prediction. However, significant discrepancies are observed for the transverse momentum of the top quark, leptons, b jets, $t\bar{t}$ system, dilepton system and $b\bar{b}$ system and invariant mass of the leptons and $t\bar{t}$ and $b\bar{b}$ systems.

The differential cross section as a function of the azimuthal angle between the two leptons, $\Delta\phi(\ell,\ell)$, is also measured and used to constrain the top quark chromomagnetic dipole moment (CMDM), using the predictions from a EFT framework for the $t\bar{t}$ production with anomalous CMDM in QCD [13]. The measurement is compatible with the SM prediction.

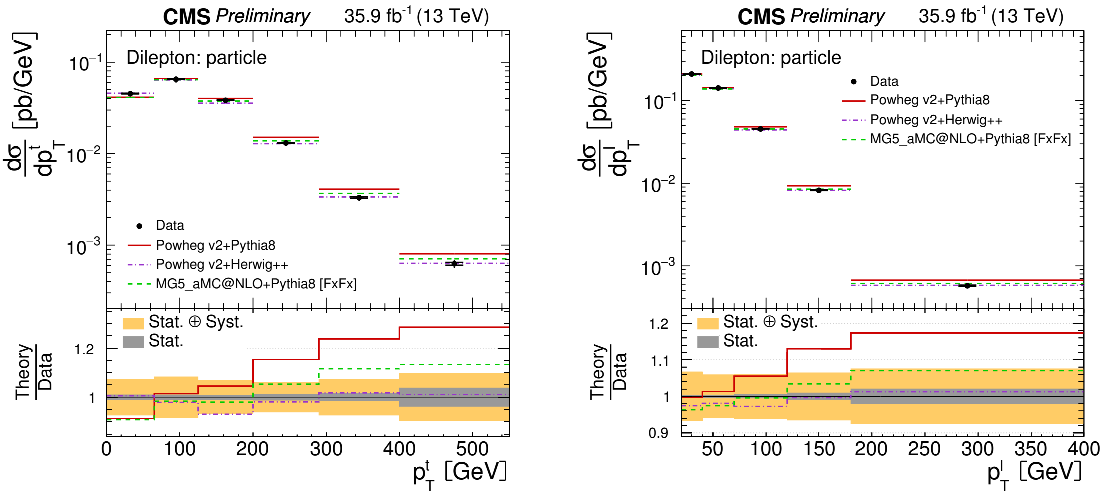

Figure 4: Differential $t\bar{t}$ cross section at particle level as a function of the top quark p_T (left) and the leading lepton p_T (right) and comparison with different simulations. [4]

4. Jet substructure in $t\bar{t}$ events

A recent measurement of the jet substructure in $t\bar{t}$ events has been performed by CMS [14] using 35.9 fb^{-1} of data at $\sqrt{s} = 13$ TeV. Events containing one electron or muon, at least two b-tagged jets and at least 4 jets are selected. The constituents of these jets are studied and several differential cross sections are measured as a function of different subjet variables such as the number of constituents, p_T dispersion, eccentricity, etc.

Different subsets of jets are considered, containing a larger proportion of b-tagged jets (bottom jets), jets coming from gluon (gluon-enriched) or coming from light quarks (light-enriched). The observations are compared with several simulations from different generators and different final state radiation tunes. In Fig. 5 the distribution of the charged multiplicity and the energy correlation ratio ($C_3^{(1)}$) are shown, for jets in the different subsets and comparison with different simulations.

None of the probed simulations has a good agreement in all the measured differential cross sections, so further tuning must be applied to the generators. Some of these differential cross sections have been used to measure the value of α_s that better fits the observed distributions, obtaining a value of $\alpha_s(M_Z) = 0.115^{+0.015}_{-0.013}$.

5. Underlying event (UE) in $t\bar{t}$ events

The underlying event in pp collisions has been measured in $t\bar{t}$ events by CMS [15] using a luminosity of 35.9 fb^{-1} at $\sqrt{s} = 13$ TeV. Events containing one electron, one muon and at least two b-tagged jets are selected. All the particles not coming from these objects are considered as constituents of the underlying event and are used to study several differential cross sections.

The measured distributions are compared with several models and variations of various modeling parameters by their uncertainties. In Fig. 6 the differential cross section as a function of the charged UE candidates is shown and it is compared with different models.

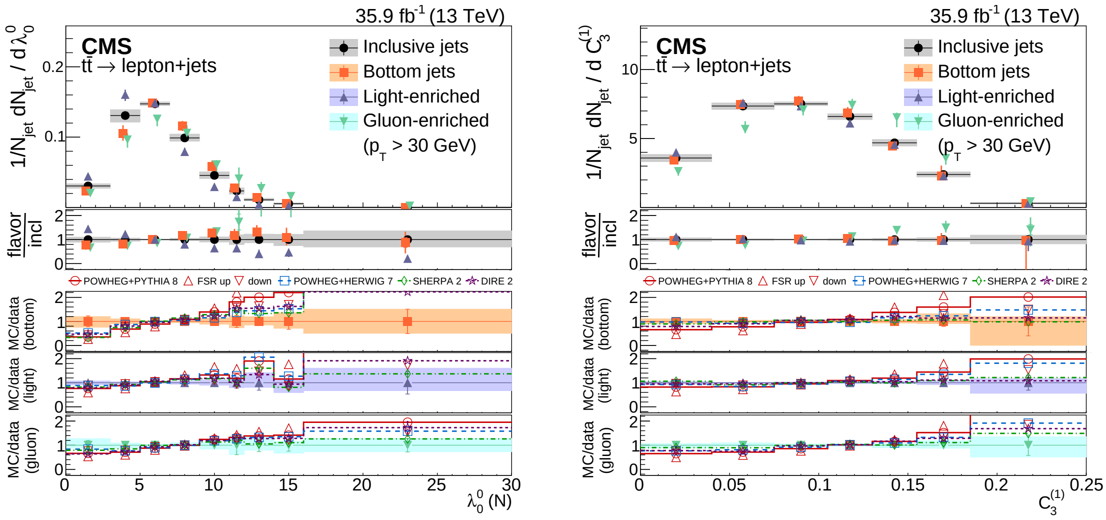

Figure 5: Distribution of charged multiplicity (left) and energy correlation ratio (right) for jets in $t\bar{t}$ events and different subsets depending on the jet flavour and comparison with different predictions. [14]

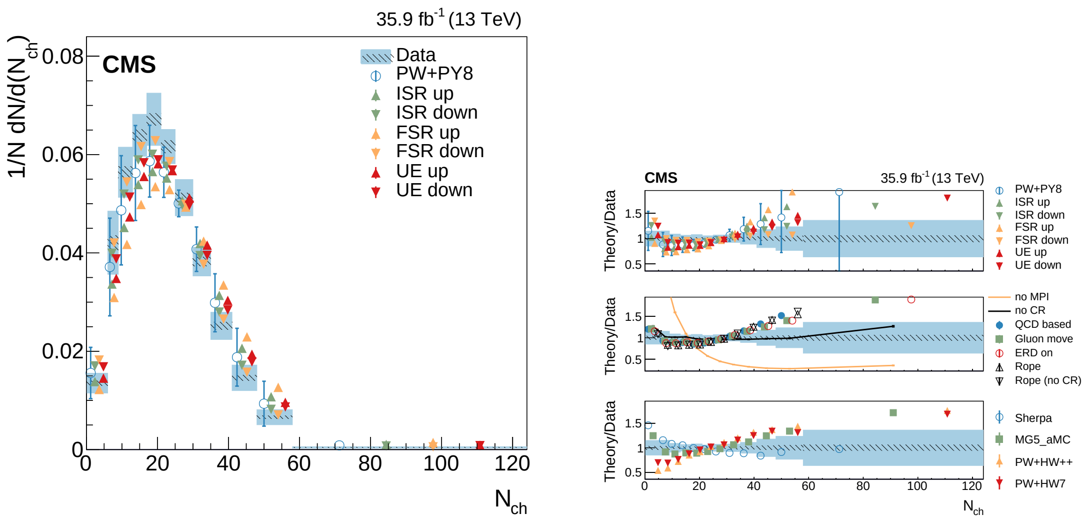

Figure 6: Distribution of number of charged UE candidates in $t\bar{t}$ events for the observed data and several predictions (left) and the theory-to-data ratios for different models (right). [15]

Most of the studied distributions are in agreement with the Powheg+Pythia $t\bar{t}$ sample with the CUETP8M2T4 tuning. These results has been also used to obtain the best fit value of $\alpha_s$from the observed distributions of the UE candidates, obtaining a value of $\alpha_s(M_Z) = 0.120 \pm 0.006$.

6. Conclusions

Inclusive $t\bar{t}$ production cross sections have been measured by CMS over a wide range of centre-of-mass energies, showing a really good agreement with QCD predictions.

Several new results on $t\bar{t}$ differential cross sections measurements have been done by CMS using the full 2016 dataset, including a study of the jet substructure in $t\bar{t}$ events and the first measurement of the underlying event in $t\bar{t}$ events. These measurements provide a really useful information about the state of the art of $t\bar{t}$ modeling for different generators and theoretical asumptions.

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PoS(LHCP2018)240