PROCEEDINGS OF SCIENCE

Top quark pair and single top differential cross sections in CMS

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Differential measurements of top quark pair and single top quark production cross sections are presented using data collected by the CMS detector. The cross sections are measured as a function of various kinematic observables of the top quarks and the jets and leptons of the event final state. The results are confronted with precise theory NLO+PS calculations.

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1. Introduction

All of the analyses that are studied in this paper concern the full LHC Run II data taking period. During this period the accelerator delivered unprecedented number of events, with almost 10^{16} proton-proton collisions at $\sqrt{s}$ = 13 TeV, corresponding to an integrated luminosity of about 163 fb^{-1}. During this period the total integrated luminosity was found to be almost 163 fb^{-1}. On average 34 interactions per bunch crossing were recorded. This large amount of data probes the Standard Model (SM) processes with high precision, allowing the detection of very rare processes and giving the possibility to explore a vast kinematic phase space.

Measurements of the differential top quark pair ($t\bar{t}$) as well as single top quark production cross sections provide important tests of the SM. Such measurements allow the determination of SM parameters and constrain the Parton Distribution Functions (PDFs) of protons. The detailed studies of the characteristics of top quark pair production as a function of different kinematic variables that can now be performed at the LHC provide a unique opportunity to test the SM at the TeV scale. Furthermore, extensions to the SM may modify the $t\bar{t}$ differential cross sections in ways that an inclusive cross section measurement is not sensitive to. In particular, such effects may distort the top quark momentum distribution, especially at higher momentum. Therefore, a precise measurement of the $t\bar{t}$ differential cross section has the potential to enhance the sensitivity to possible effects beyond the SM as well as challenge theoretical predictions that now reach next-to-next-to-leading-order (NNLO) accuracy in perturbative quantum chromodynamics (pQCD). Moreover, the differential distributions are sensitive to the differences between Monte Carlo (MC) generators and their settings, representing valuable input to the tuning of the MC parameters.

Single top quark measurements provide tests of electroweak interactions and sensitivity to up and down quark PDFs. All three production modes are sensitive to the tWb-vertex and hence new physics. For example, tW production is useful in W' and charged Higgs searches and t-channel production can be used to look for flavor changing neutral currents (FCNCs). In addition, single top quark is background to Higgs boson and new physics searches.

2. Top pair differential Cross Sections

2.1 Boosted Differential Cross Section

2.1.1 Hadronic Channel

This analysis probes the all hadronic decay channel where both W bosons coming from the top quark decay into quarks resulting into high-p_{T} hadronic final states (jets). When jets are boosted (high p_{T}) the decay products are collimated. The motivation here is to explore the kinematic region beyond the reach of the resolved analyses of angularly resolved decay products.

The selection is based on the construction of a Neural Network (NN) classifier that discriminates signal from background using jet substructure properties. The analysis calculates both absolute and normalised differential cross sections at parton and particle levels with respect to top and top pair kinematic variables. In Fig. 1 the results of the normalised differential cross sections are shown at parton level with respect to the top quark and the $t\bar{t}$ system kinematic variables. The results are compatible with theory. It is worth mentioning that there is an overprediction of the order of 35% in the total cross section in this regime.

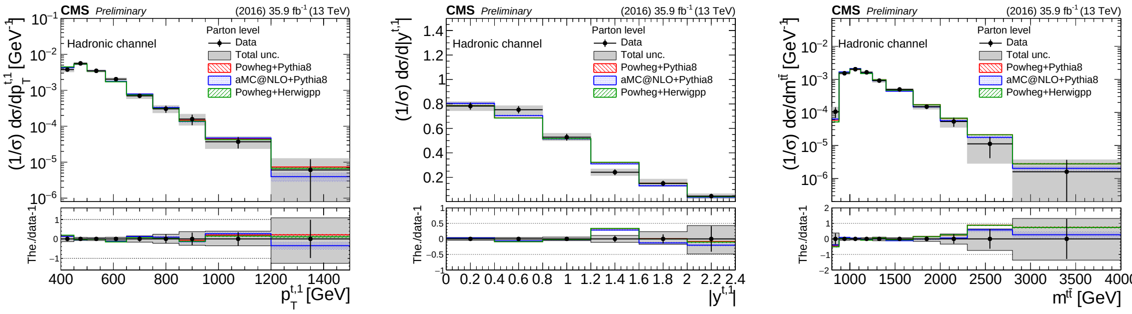

Figure 1: Results of the normalised differential cross sections are shown at parton level with respect to the leading jet p_T (left), the leading jet absolute rapidity |y| (middle) and the mass of the $t\bar{t}$ pair (right).[2]

2.1.2 Lepton + jets

The same analysis also probes the semi-leptonic (lepton + jets) channel for high p_{T} jets, in which one W boson decays into a lepton and a neutrino and the other decays into two quarks. The selection here is based on top quark and b quark jet categories to distinguish signal from background.

Both absolute and normalised differential cross sections are calculated at parton and particle levels as a function of the hadronically decaying top quark p_{T} and rapidity. The results in Fig. 2 show the parton level normalised differential cross section calculations as a function of the top quark p_{T} and absolute rapidity. The differential distributions are well described, but all models over predict the absolute cross section by almost 20%.

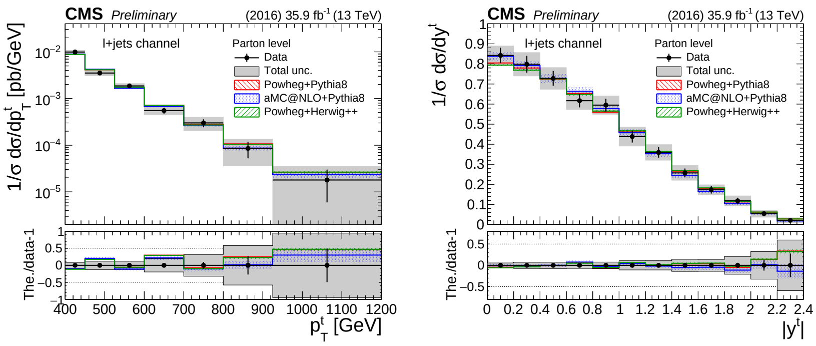

Figure 2: Parton level normalised differential cross section calculations as a function of the top quark p_T (left) and absolute rapidity (right). [2]

2.2 Multi-Differential Cross Sections

Here we present the top quark pair multi-differential cross sections. In this analysis both the double and triple normalised differential cross sections are measured in the dilepton channel, where both top quarks decay into a lepton and a neutrino, using the 2016 data. The motivation for this analysis comes from the assumption that the $t\bar{t}$ cross sections can be used to extract the PDFs (constraining high-x gluon contribution). Via this analysis it is also possible to constrain fundamental SM parameters such as the strong coupling strength a_{S} and the top quark pole mass

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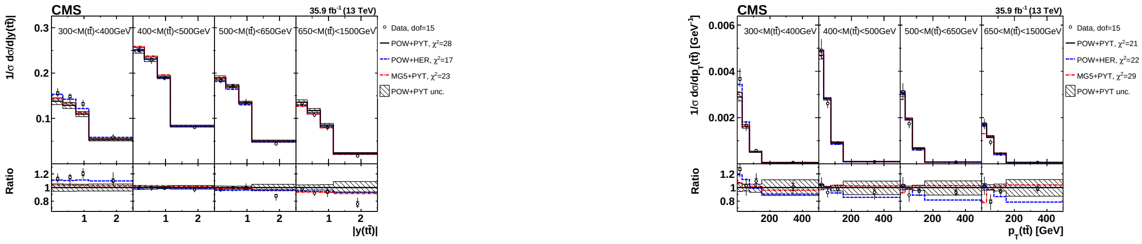

Figure 3: Results of the double differential cross sections. Absolute $t\bar{t}$ pair rapidity (left) and p_T (right) are presented in various $t\bar{t}$ pair mass ranges. [3]

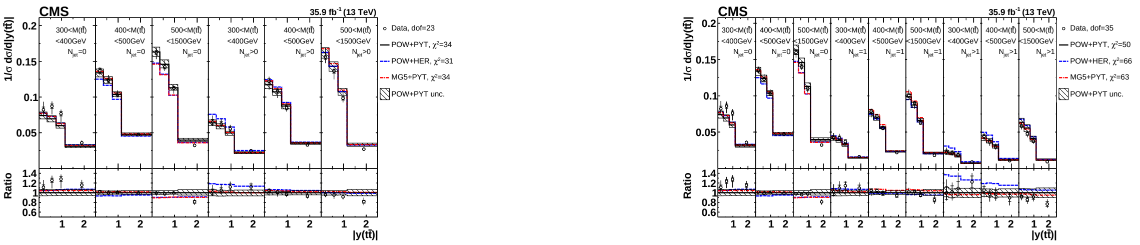

Figure 4: Triple differential normalised cross section at parton level as a function of the absolute $t\bar{t}$ rapidity (|y|) in different top quark pair mass ranges and N_{jet} ranges measured using 2 bins (0 jets, at least 1 jet) (left) and 3 bins (0 jets, 1jet, at least 1 jet) (right) [3]

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m_t^{pole}. The selection in this analysis requires 2 opposite charged leptons and 2 jets from which at least 1 must be b-tagged. A quantitative comparison to several MC predictions is presented at parton level, where data can reveal trends and can distinguish between predictions. The calculation of the strong coupling strength a_S, the top quark pole mass m_t^{pole} and the PDFs can be constrained in the measurement of the triple differential production cross section. Up to this date, this measurement of the top quark pole mass is the most precise.

2.2.1 2D-Differential Cross Sections

Fig 3 shows the results of the double differential cross sections in the dilepton channel. More specifically the absolute $t\bar{t}$ pair rapidity is presented in various $t\bar{t}$ pair mass ranges. The shapes are well described in general except in the region of the high $t\bar{t}$ invariant mass. The best description is given by Powheg + Herwig++.

2.2.2 3D-Differential Cross Sections

In this section we present the results of the triple differential cross sections. Fig. 4 illustrates the triple differential normalised cross section at parton level as a function of the absolute $t\bar{t}$ rapidity in different invariant $t\bar{t}$ mass ranges and number of jet (N_{jet}) (where N_{jet} is the number of extra jets not arising from the decay of the $t\bar{t}$ system) ranges measured using 2 bins (0 jets, at least 1 jet). For this measurement only the Powheg+Pythia is in satisfactory agreement with the data. Powheg + Herwig++ predicts a higher cross section for $N_{\text{jet}} > 1$, while the MG5 + Pythia provides an unsatisfactory description of the invariant $t\bar{t}$ mass distribution for exactly 1 jet (N_{jet} =1).

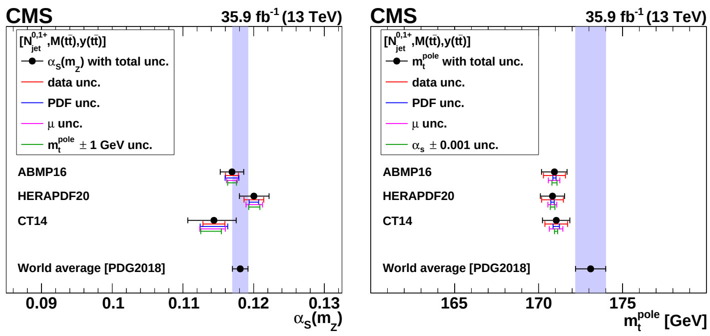

Figure 5: Extracted strong coupling strength α_S (left) and top quark pole mass m_t^{pole} (right). [3]

2.2.3 Extraction of α_S, m_t^{pole} and PDFs from 3D Cross Sections

We present the calculation of the strong coupling strength and top quark pole mass from the triple differential cross sections of the absolute $t\bar{t}$ rapidity in different $m_{t\bar{t}}$ ranges and N_{jet} in two bins. To extract the strong coupling strength and the top quark pole mass, the measured triple differential cross sections are compared to fixed next-to-leading order (NLO) predictions.

The measured cross sections are compared to NLO predictions obtained using different PDF sets, top quark pole mass values and strong coupling strength values. The values of the strong coupling strength and the top quark pole mass are extracted by calculating the χ^2 between data and NLO predictions as a function of the input strong coupling strength (α_S) or top quark pole mass and approximating the dependence with a parabola. The minimum of this parabola is taken to be the extracted strong coupling strength or top quark pole mass.

The extracted values are compared to the world average. In Fig. 5 (left) we present the extracted strong coupling strength, for which we used a top quark pole mass with a value of 172.5 GeV. The extraction allows precise determination of the α_S and there is significant dependence on the PDF. Also, Fig 5 (right) shows the extracted top quark pole mass, for which we used the strong coupling strength obtained for each PDF set. The extraction allows precise determination of the top quark pole mass and as one can observe there is no significant dependence on the used PDF set.

The triple differential normalised cross section [N_{jet}0,1+,invariant $t\bar{t}$ mass, $t\bar{t}$ rapidity] is used in a simultaneous PDF, strong coupling strength α_S and top quark pole mass m_t^{pole} fit at NLO together with the combined HERA inclusive deep inelastic scattering data. Fig. 6 shows the results of this measurement.

3. Single Top Differential Cross Sections

In this section we present the differential cross sections for both the t-channel and the tW production mode. Also, for the t-channel measurements, the charge ratios and spin asymmetry are calculated.

3.1 Single top Differential Cross Section in the t-channel

This analysis studies the single (anti) top quark production in the t-channel. More specifically, the selection consists of events containing single muons or electrons and two or three jets. As for

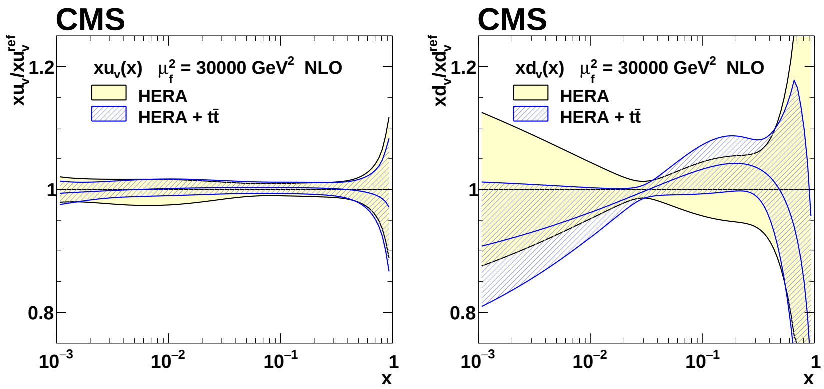

Figure 6: PDFs with their total uncertainties obtained from a simultaneous fit on PDFs, strong coupling strength and top quark pole mass variations using HERA inclusive deep inelastic scattering (DIS) data only and HERA DIS + $t\bar{t}$ data, as a function of χ, where χ is the fraction of the proton momentum carried by a parton. [3]

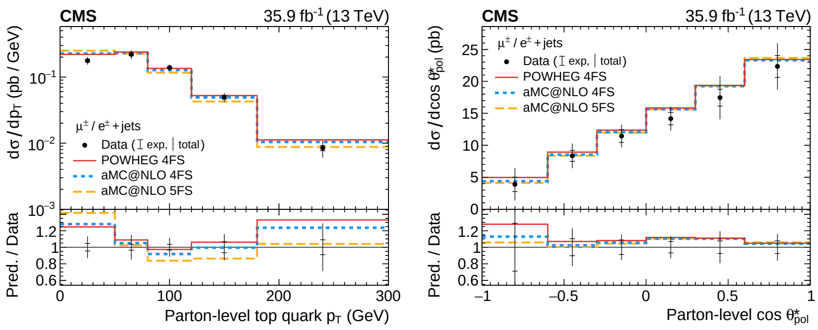

Figure 7: Parton level absolute cross sections as a function of the top quark p_T and the cosine of the polarisation angle $cos\theta^*_{\mathrm{pol}}$. [4]

the measurements, both absolute and normalised differential cross sections at parton and particle levels are calculated with respect to top quark p_T, rapidity and polarisation angle $cos\theta_{pol.}{}^* = \frac{\vec{p}_{q'}^{(top)} \vec{p}_{l}^{(top)}}{|\vec{p}_{q'}^{(top)}| \cdot |\vec{p}_{l}^{(top)}|}$. The measurements are also presented as a function of the charged lepton p_T and rapidity and the W boson p_T from the top quark decay. In general the results are in agreement with predictions using various NLO generators and various sets of PDFs. Parton level results are presented in Fig. 7.

3.1.1 Charge Ratios

The same analysis also calculates the charge ratios as a function of several observables both at parton and particle levels. As charge ratio we define the ratio of the single top cross sections to the sum of the single top quark and antiquark cross section. It is measured differentially as a function of the top quark, the charged lepton and the W boson kinematic observables. Fig. 8 shows the charge ratio calculations at parton level.

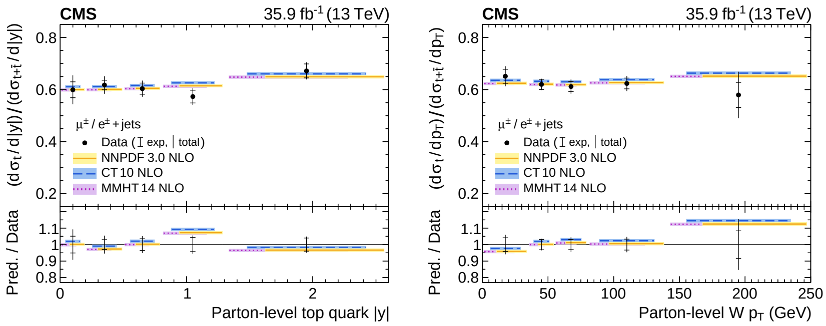

Figure 8: Charge ratio distributions at parton level as a function of the absolute top quark rapidity (left) and the W boson p_T (right). [4]

3.1.2 Spin Assymetry

The spin asymmetry, a value sensitive to the top quark polarisation, is calculated for the single top quark in the t-channel using the polarisation angle distributions. It is sensitive to top quark polarisation and is determined from the differential distribution of the polarisation angle at parton level. The spin asymmetry is measured to be 0.440 ± 0.070 for the combined electron and muon channel, 0.446 ± 0.099 for the muon channel and 0.403 ± 0.071 for the electron channel. The measured asymmetries are found to be in agreement with the predicted value of 0.436 found using PowHeg @ NLO (with negligible uncertainty).

3.2 Single top Differential Cross Section – tW production mode

This analysis measures single top differential cross sections in the tW production mode. The main challenge of this analysis is that background dominates signal with $t\bar{t}$ being the largest. The signal extraction is performed by subtracting the background contribution which is estimated through MC simulations. Both absolute and normalised differential cross sections are measured at particle level with respect to the p_T of both the lepton and the jet, the $\Delta\phi$ of the two leptons, the invariant mass of the two leptons and the jet, the transverse mass of the 2 leptons + 1 jet + missing energy system and the longitudinal component of the formed 2 leptons + jet system. Figure 9 shows some of the results of the analysis.

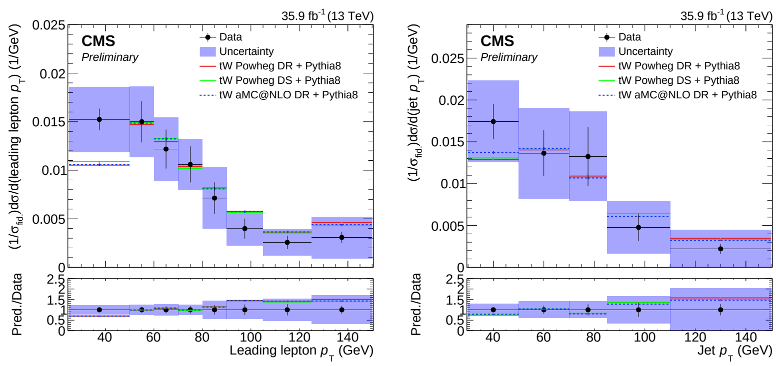

Figure 9: Normalised differential cross sections at particle level, as a function of the leading lepton p_T (left) and the jet p_T (right). [5]

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