PROCEEDINGS OF SCIENCE

Top Quark Pair Cross Section Measurements with CMS Detector

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This document presents the latest results in the measurement of the top-quark pair production cross section obtained with data collected by the CMS detector at LHC accelerator. The analyses are performed in the dilepton, single lepton and full hadronic decay modes. Additionally to the inclusive measurements of $\sigma_{t\bar{t}}$ at 7, 8 and 13 TeV, the CMS collaboration provides for the first time the cross section at 5.02 TeV. Results are confronted with the latest and most precise theoretical calculations.

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1. Introduction

The top quark, with a mass about 173.3 GeV[1], plays an important role in the study of the electroweak symmetry breaking (Higgs boson) as well as in the search of physics beyond the standard model (BSM). The production of top quark anti-quark pairs is one of the main backgrounds in many of the processes related with the standard model (SM) and BSM, making crucial to measure its production cross section with very high precision.

The Large Hadron Collider (LHC) is operating since 2009, producing proton-proton (ion-ion) collisions with a centre-of-mass energy of 7, 8 TeV, and since 2015, 13 TeV. This document presents the most recent measurements of the inclusive and differential $\mathrm{t\bar{t}}$ cross section with data collected by the CMS detector[2].

Section 2 presents results in the dilepton decay mode. This channel yields the best precision in the measurement of the inclusive $\mathrm{t\bar{t}}$ cross section due to the small amount of background, specially in the muon-electron final state and due to a typically lower extrapolation factor by reason of its loose selection. Section 3 contains the latest results in the single lepton channel. It provides a precise way to extract the differential $\mathrm{t\bar{t}}$ cross section due to the fact that it involves only one neutrino in its decay chain. Finally, Section 4 presents the measurements performed in the full hadronic decay mode, a very challenging channel due to the large background contribution from QCD processes.

2. Dilepton Decay Mode

2.1 Inclusive $\mathrm{t\bar{t}}$ cross section at 7 and 8 TeV[3]

This analysis, performed with all the available data collected at 7 and 8 TeV extracts the inclusive $\mathrm{t\bar{t}}$ cross section with an extended binned likelihood fit. The fit is performed over signal and background contributions to multi-differential binned distributions related to the jet and b-jet multiplicity and transverse momenta of other jets in the event.

Figure 1 shows the p_T of the least energetic additional non b-jet in the event for events with one, two, and at least three additional non b-jets. The obtained results for the inclusive $\sigma_{\mathrm{t\bar{t}}}$ at the two centre-of-mass energies is:

$$\begin{aligned}\sigma_{\mathrm{t\bar{t}}(7\ \mathrm{TeV})} &= 174.5 \pm 2.1(\mathrm{stat.}) \pm^{4.5}_{4.0}(\mathrm{syst.}) \pm 3.8(\mathrm{Lumi.})\ \mathrm{pb} \\ \sigma_{\mathrm{t\bar{t}}(8\ \mathrm{TeV})} &= 245.6 \pm 1.3(\mathrm{stat.}) \pm^{6.6}_{5.5}(\mathrm{syst.}) \pm 6.5(\mathrm{Lumi.})\ \mathrm{pb}\end{aligned} \tag{2.1}$$

2.2 Inclusive $\mathrm{t\bar{t}}$ cross section at 13 TeV[4]

The amount of data studied to produce the first measurement of the inclusive top quark anti-quark cross section at 13 TeV correspond to 2.2 fb^{-1}. The $\sigma_{\mathrm{t\bar{t}}}$ extraction is performed in the muon-electron decay mode using a robust cut-based analysis method. Figure 2 shows the jet and b-jet multiplicity distributions for events with at least two opposite charge leptons. The measurement for the inclusive $\mathrm{t\bar{t}}$ cross section at 13 TeV yields:

$$\sigma_{\mathrm{t\bar{t}}} = 793 \pm 8(\mathrm{stat.}) \pm 38(\mathrm{syst.}) \pm 21(\mathrm{Lumi.})\ \mathrm{pb} \tag{2.2}$$

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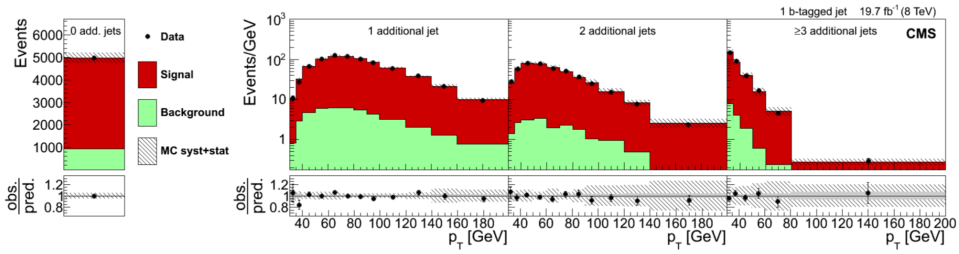

Figure 1: p_T of the least energetic additional non b-jet for events with one b-jet and one, two, and at least three additional non b-jets at $\sqrt{s} = 8$ TeV. The hatched bands correspond to the total uncertainty on the sum of the predicted yields after the fit.

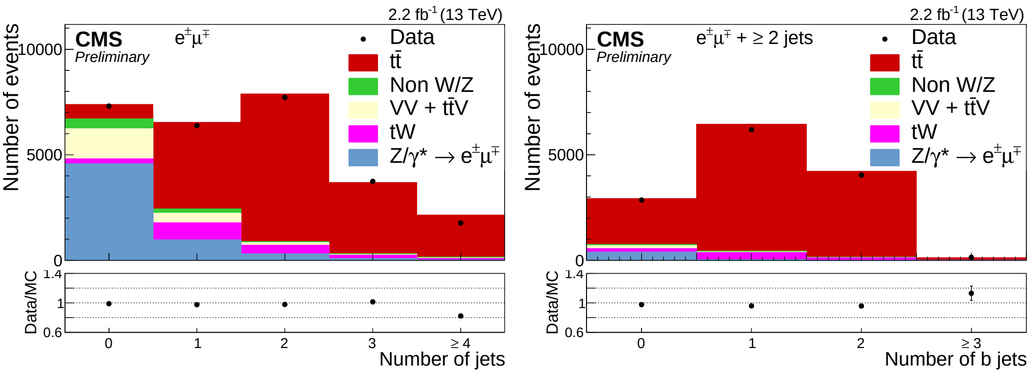

Figure 2: Jet (left) and b-tagged jet (right) multiplicities in the eμ channel at 13 TeV

2.3 Inclusive $\mathrm{t\bar{t}}$ cross section at 5.02 TeV[5]

At the end of 2015, the LHC delivered 26 pb^{-1} of proton-proton collisions at centre-of-mass energy of 5.02 TeV. It produced an oportunity to measure for the first time the inclusive $\sigma_{\mathrm{t\bar{t}}}$ in order to provide a new comparison with the current theoretical prediction as well as a reference measurement for the nuclear collisions at the same nucleon-nucleon centre-of-mass energy without need to extrapolate from measurements at different energy.

Figure 3 shows the jet multiplicity and the dilepton p_T distributions after require events with a muon-electron pair with opposite charge and at least two jets (cut not included in the jet multiplicity plot). The inclusive $\mathrm{t\bar{t}}$ cross section at 5.02 TeV with its corresponding statistical and systematic uncertainties is:

$$\sigma_{\mathrm{t\bar{t}}} = 82 \pm 20(\mathrm{stat.}) \pm 5(\mathrm{syst.}) \pm 10(\mathrm{Lumi.})\ \mathrm{pb} \tag{2.3}$$

2.4 Differential $\mathrm{t\bar{t}}$ cross section at 13 TeV[6]

This analysis presents the differential $\mathrm{t\bar{t}}$ cross section at $\sqrt{s} = 13$ TeV performed in the three dilepton decay modes ($\mu\mu$, ee and μe). Even if the dilepton channel does not have a fully contrained system, due to the two neutrinos from the W decay, the efficiency for the kinematic reconstruction in this analysis reaches a 90%, improving the presicion of the measurement. Figure 4

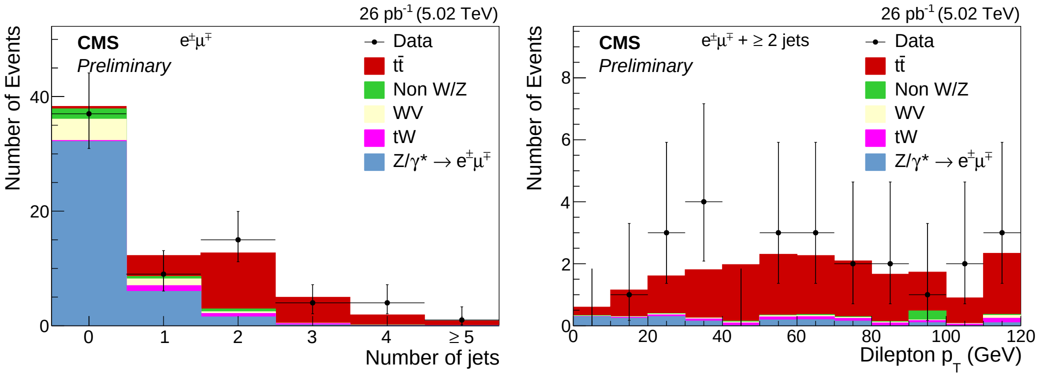

Figure 3: Distributions of the jet multiplicity and p_T of the dilepton system after require a muon-electron pair (left) plus at least two jets (right).

shows the normalized differential $\sigma_{t\bar{t}}$ as a function of the jet multiplicity, p_T^t of the top (anti) quark and rapidity distributions of the top quark pair.

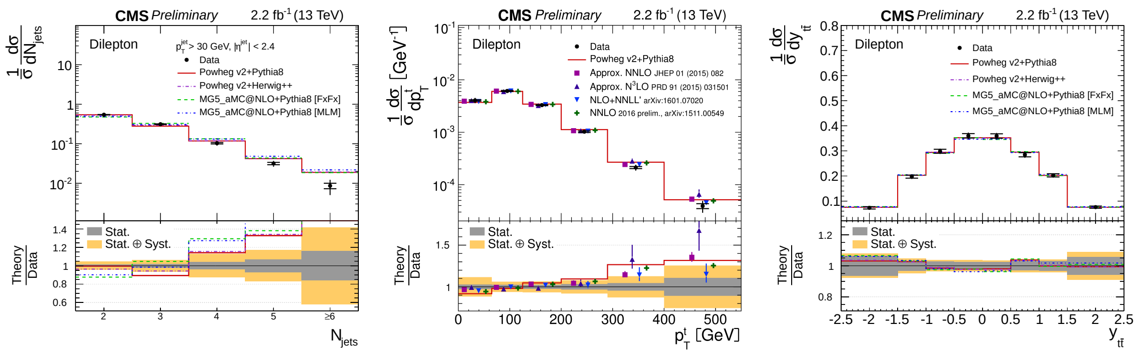

Figure 4: Normalized differential $t\bar{t}$ production cross section as a function of the jet multiplicity (left), p_T^t of the top (anti) quark (middle) and rapidity distributions (right) of the top quark pair. The data are compared to the available MC predictions.

3. Single Lepton Decay Mode

3.1 Legacy measurement at 7 and 8 TeV[7]

In order to complement all the measurements performed during Run I of the LHC accelerator, CMS has also performed a legacy analysis in order to measure the inclusive $t\bar{t}$ cross section using the single lepton decay mode. This study is performed with the full available sample at $\sqrt{s} = 7$ and 8 TeV. The extraction of $\sigma_{t\bar{t}}$ is done with two different approaches: fitting the invariant mass of the lepton plus b-jet system ($M_{\ell b}$) and a fit over the mass of the three jets with highest p_T (M_3). Figure 5 shows $M_{\ell b}$ and M_3 variables, being the measured values at 7 and 8 TeV and the corresponding ratio:

$$
\begin{aligned}
\sigma_{t\bar{t}(7\ \mathrm{TeV})} &= 161.7 \pm 6.0(\mathrm{stat.}) \pm 12.0(\mathrm{syst.}) \pm 3.6(\mathrm{Lumi.})\ \mathrm{pb} \\
\sigma_{t\bar{t}(8\ \mathrm{TeV})} &= 228.5 \pm 3.8(\mathrm{stat.}) \pm 13.7(\mathrm{syst.}) \pm 6.0(\mathrm{Lumi.})\ \mathrm{pb} \\
R_{(8/7)\ \mathrm{TeV}} &= 1.43 \pm 0.04(\mathrm{stat.}) \pm 0.07(\mathrm{syst.}) \pm 0.05(\mathrm{Lumi.})\ \mathrm{pb}
\end{aligned}
\tag{3.1}
$$

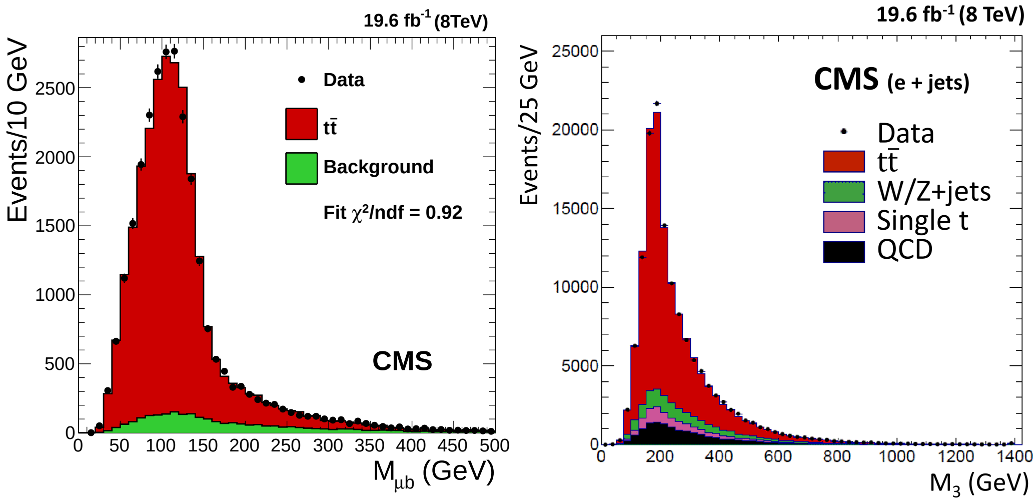

Figure 5: Template fit result on the $M_{\ell b}$ in the muon + jets channel (left) and M_3 in the electron + jets channel (right). Signal and background contributions are rescaled according to the fit results.

3.2 Differential $t\bar{t}$ cross section at 13 TeV

3.2.1 Differential $t\bar{t}$ cross section in Fiducial volume[8]

This analysis performs the measurement of the differential $t\bar{t}$ cross section over event variables that do not need the full reconstruction of the $t\bar{t}$ event. The event selection requires one lepton well identified and isolated, at least 4 jets, where at least two of them must be identified as b-jets. Figure 6 shows the measured normalized differential cross section with respect to H_T, missing transverse energy and jet multiplicity.

3.2.2 Differential $t\bar{t}$ cross section in single lepton channel[9]

Exploting the fact that the single lepton channel provides an excellent scenario to reconstruct the $t\bar{t}$ decay channel, CMS has performed a precise analysis to measure the diferential $t\bar{t}$ cross section with the first 2.3 fb^{-1} of data collected at $\sqrt{s} = 13$ TeV. The reconstruction of the $t\bar{t}$ system has been improved choosing the neutrino momentum solution where the W-boson and top-quark mass were constrained. Figure 7 presents the differential cross section at parton level as a function of p_T of the top (anti) quark and the invariant mass of the $t\bar{t}$ pair, and the differential cross section at particle level as a function of the rapidity of $t\bar{t}$ system.

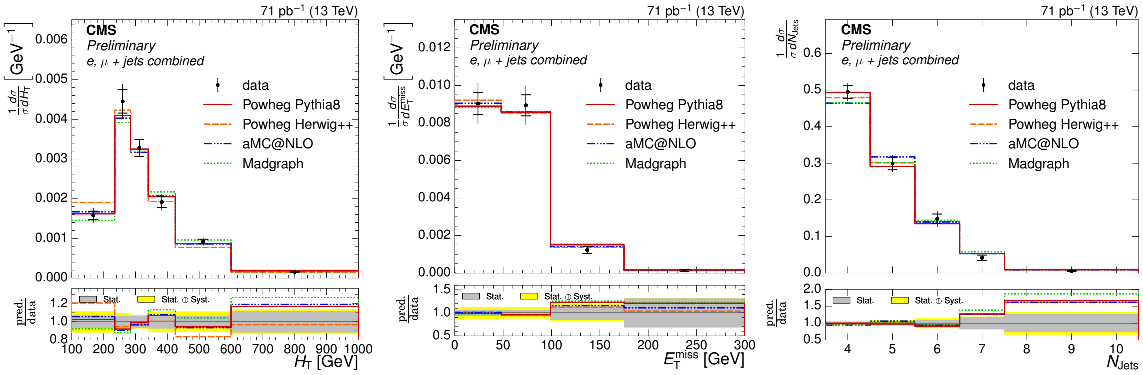

Figure 6: Comparison of measured normalized differential cross section with respect to H_T, E_T^{miss} and number of jets to different event generators for the combined channel at $\sqrt{s} = 13$ TeV. The inner vertical bars denote the statistical uncertainty, while the outer bar the total uncertainty.

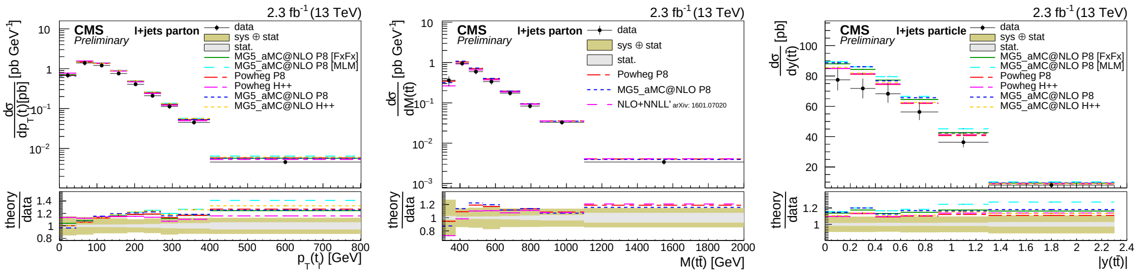

Figure 7: Differential $\mathrm{t\bar{t}}$ cross sections at parton level as a function of $p_T(\mathrm{t})$ (left), $M(\mathrm{t\bar{t}})$ (middle) and differential $\mathrm{t\bar{t}}$ cross sections at particle level with respect to $y(\mathrm{t\bar{t}})$ (right). Distributions are compared to the MC predictions.

4. All Jets Decay Mode

4.1 Inclusive Differential $\mathrm{t\bar{t}}$ cross section in all jets channel[10]

The measurement of the $\mathrm{t\bar{t}}$ cross section in the all-jets channel is complementary to the ones in the leptonic modes due to its unique ability to reconstruct fully the $\mathrm{t\bar{t}}$ system. The presence of multiple jets in the final state also involves larger uncertainties from the jet energy scale and the b-jet identification compared with the results presented before.

The analysis follows two complementary reconstruction approaches, the resolved and the boosted, which are applied as a funtion of the top quark p_T. When the top quarks are not significantly boosted in the laboratory frame, their decay products can be reconstructed individually, therefore allowing for a resolved analysis to be performed. On the other hand, the boosted technique applies to events with high-p_T top quarks whose decay products are merged in a unique jet. The combination of the two techniques effectively increases the p_T region up to reach the TeV scale.

Figure 8 shows the differential $\mathrm{t\bar{t}}$ cross section as a function of the leading top quark p_T in the resolved and the boosted analysis. The inclusive $\mathrm{t\bar{t}}$ cross sections, extracted after extrapolating to the full phase space the resolved and boosted analysis, are found to be in agreement with each other:

$$\sigma_{\mathrm{t\bar{t}(resolved)}} = 834 \pm 25(\mathrm{stat})^{+118}_{-104}(\mathrm{syst}) \pm 23(\mathrm{lumi})\,\mathrm{pb}$$
$$\sigma_{\mathrm{t\bar{t}(boosted)}} = 727 \pm 46(\mathrm{stat})^{+115}_{-112}(\mathrm{syst}) \pm 20(\mathrm{lumi})\,\mathrm{pb} \quad (4.1)$$

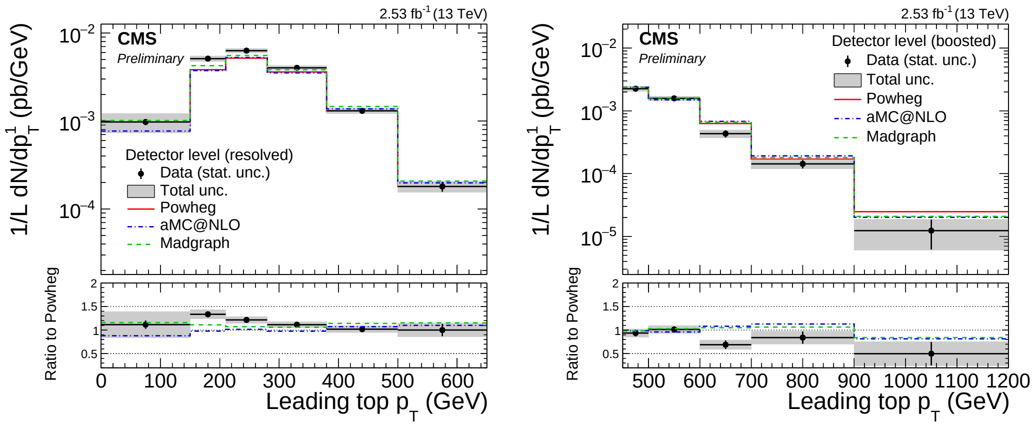

Figure 8: Differential $\mathrm{t\bar{t}}$ cross section as a function of the leading top quark p_T in the resolved (left) and the boosted (right) analysis.

5. Summary

The LHC has a strong program in the measurement of the top quark properties, especially in the differential and inclusive $\mathrm{t\bar{t}}$ production cross section. The results presented in this talk have reached unprecedented precisions, challenging the current theoretical predictions at NLO and NNLO. Figure 9 shows the summary of the measurements performed by CMS detectors at 5.02, 7, 8 and 13 TeV compared with the lastest theoretical calculations and the full phase-space normalized differential $\mathrm{t\bar{t}}$ cross section as a function of the transverse momentum of the top-quark[11]. All results are found to be in agreement with the standard model prediction.

References

[1] ATLAS, CDF, CMS, DØ Collaboration, "First combination of Tevatron and LHC measurements of the top-quark mass", arXiv:1403.4427.

[2] CMS Collaboration, "The CMS experiment at the CERN LHC", JINST 3 (2008) S08004.

[3] CMS Collaboration, "Measurement of the $\mathrm{t\bar{t}}$ production cross section in the eμ channel in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV", JHEP 08 (2016) 029.

[4] CMS Collaboration, "Measurement of the top quark pair production cross section using eμ events in proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS detector", CMS-PAS-TOP-16-005.

[5] CMS Collaboration, "First measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s} = 5.02$ TeV", CMS-PAS-TOP-16-015.

[6] CMS Collaboration, "Measurement of the differential cross section for $\mathrm{t\bar{t}}$ production in the dilepton final state at $\sqrt{s} = 13$ TeV", CMS-PAS-TOP-16-011.

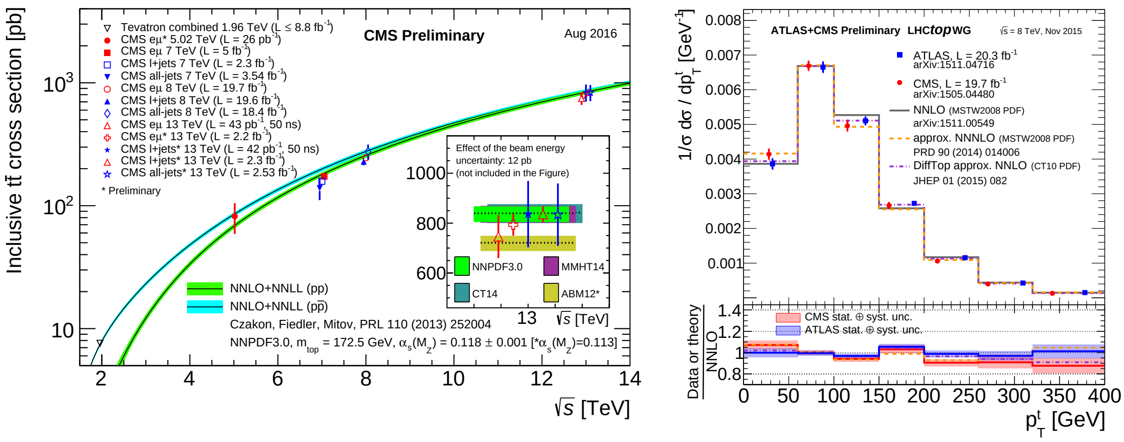

Figure 9: Inclusive and differential[11] top quark pair cross section of the most precise CMS measurements in the different decay modes compared with the theoretical predictions.

[7] CMS Collaboration, "Measurements of the $t\bar{t}$ production cross section in lepton+jets final states in pp collisions at 8 TeV and ratio of 8 to 7 TeV cross sections", arXiv:1602.09024 [hep-ex] (Submitted to EPJC).

[8] CMS Collaboration, "Measurement of differential top quark pair production cross sections in a fiducial volume as a function of event variables in pp collisions at $\sqrt{s} = 13$ TeV", CMS-PAS-TOP-15-013.

[9] CMS Collaboration, "Measurement of the inclusive and differential $t\bar{t}$ production cross sections in lepton + jets final states at 13 TeV", CMS-PAS-TOP-16-008.

[10] CMS Collaboration, "Measurement of the $t\bar{t}$ production cross section at 13 TeV in the all-jets final state", CMS-PAS-TOP-16-013.

[11] LHC TOP Working Group, "Summary plots for the inclusive and differential $t\bar{t}$ cross section", twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots