IL NUOVO CIMENTO Vol. 37 C, N. 6 Novembre-Dicembre 2014
DOI 10.1393/ncc/i2015-11857-x

Colloquia: LaThuile14

Top quark production at CMS

C. Diez Pardos for the CMS Collaboration
Deutsches Elektronen Synkrotron (DESY) - Notkestrasse 85, 22607, Hamburg, Germany

ricevuto il 31 Luglio 2014

Summary. — An overview of recent measurements of top quark pair production is presented, including inclusive cross sections as well as differential distributions. The production of single top quarks via the three processes, t-channel, s-channel, and tW associated production is also discussed. The results are obtained using data collected with the CMS experiment in proton-proton collisions at centre-of-mass energies of 7 TeV and 8 TeV.

PACS 14.65.Ha – Top quarks.

1. – Introduction

The top quark is the heaviest known elementary particle and the only quark that decays before hadronisation, and thus gives direct access to its properties. With its large mass, it plays a crucial role in electroweak loop corrections, providing indirect constraints on the mass of the Higgs boson. Top quark measurements also provide important input to QCD calculations. Moreover, various scenarios of physics beyond the standard model (SM) expect the top quark to couple to new particles.

Top quarks are mostly produced in pairs via strong interaction in hadron colliders. At the LHC energies, the dominant mechanism is gluon-gluon fusion, corresponding to about 80% of the generation process. Top quarks can also be produced singly, via electroweak interaction. The three modes of single top quark production are t-channel, tW associated production and s-channel.

Top quarks decay almost exclusively via the $t \to bW$ and it is the decay of the W bosons what defines the final state. Therefore, top-quark-pair ($t\bar{t}$) signatures can be classified according to the combinatorics of the W boson decay. Thus, $t\bar{t}$ final states include events with two leptons, two neutrinos and two b jets (dileptonic), with one lepton, one neutrino and four jets, out of which two arise from a b quark (lepton+jets) or with six jets, out of which two stem from a b quark (all-hadronic channel).

In the following the main analyses of top quark production performed at CMS [1] are summarised, focusing on the measurements obtained with data collected at 8 TeV. Details of additional analyses at 8 TeV and 7 TeV not described here can be found in [2].

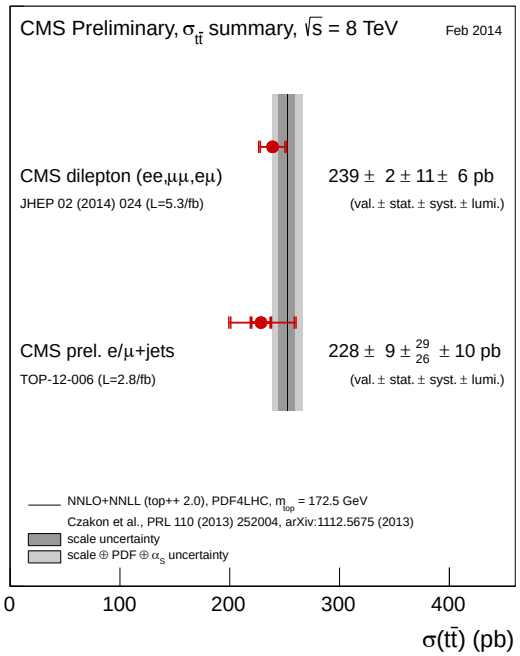

Fig. 1. – $t\bar{t}$ production cross section summary figure (8 TeV), compared with approximate NNLO and full NNLO calculations.

The $t\bar{t}$ measurements presented are performed in the lepton+jets or/and dilepton decay channels. The single top quark analyses consider only the leptonic decay cascade of the top quark.

2. – $t\bar{t}$ production

2˙1. *Inclusive $\sigma(t\bar{t})$ production cross section.* – CMS has measured at 8 TeV $\sigma(t\bar{t})$ in the dilepton decay channels and lepton+jets channels. In the former, the cross section is extracted after a cut-based selection and data-driven background subtraction [3]. In the later, $\sigma(t\bar{t})$ is obtained using maximum likelihood fits to topological or kinematic variables [4]. Both measurements are dominated by the systematic uncertainty, the dominant sources are signal modelling and jet energy scale uncertainties. The results are in good agreement with NLO and approximate NNLO calculations, as shown in fig. 1.

2˙2. *Differential cross section measurements.* – Differential measurements as a function of top quark related kinematic quantities are tests of perturbative QCD (pQCD) and probe a variety of different properties, for instance the $p_{t\bar{t}}$ distribution is sensitive to higher order effects like initial/final state radiation of quarks or gluons. Moreover possible deviations in the shapes of all distributions can hint at physics beyond the SM. A measurement of $t\bar{t}$+jets also represents a test of pQCD and the understanding of these processes is important not least because multijet processes constitute important backgrounds for many new physics searches and $t\bar{t}+H$ processes.

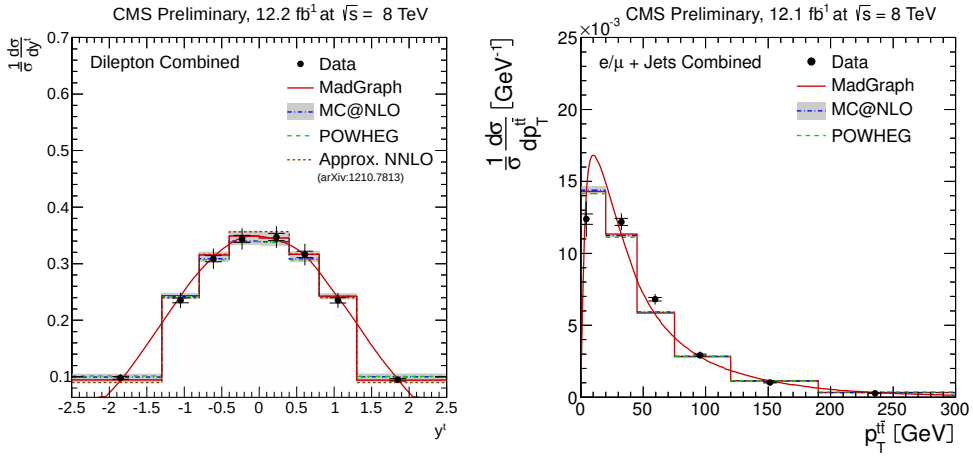

Fig. 2. – $t\bar{t}$ production normalised differential cross section as a function of y_t (left) and $p_{t\bar{t}}$ (right), compared to predictions from MadGraph and POWHEG interfaced with Pythia and MC@NLO interfaced with Herwig.

CMS has performed several measurements of $t\bar{t}$ production differential measurements, such as the cross section as a function of kinematic quantities of the top quark itself, the $t\bar{t}$ system and its decay products [5,6], as well as exclusive measurements of $t\bar{t}$ pairs produced in association with other objects like jets [7] (dilepton decay channels) or global event variables [8] (lepton+jets decay channel). The measurements are corrected for detector and hadronisation effects back to parton level, using a regularised unfolding procedure, and they are normalised, so that systematic uncertainties correlated between all bins cancel in the ratio. Figures 2 and 3 show examples of those distributions compared to different theory models. In general good agreement is observed between data and predictions.

2˙3. *$t\bar{t} + b\bar{b}$ production.* – The production of $t\bar{t}$ in association with a pair of bottom quarks ($b\bar{b}$) is an irreducible background to the production of $t\bar{t} + H$, where the Higgs boson decays to $b\bar{b}$. A precise measurement of $\sigma(t\bar{t}b\bar{b})$ has the potential to reduce background uncertainty and thus, increase sensitivity. CMS has measured the cross section ratio $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ using events with two leptons and four reconstructed jets. The relative contribution from $t\bar{t}b\bar{b}$ is determined from a fit to the measured b-tagging algorithm discriminators of the leading (in p_{T}) additional jets in the event, see fig. 4. The results, obtained for two different p_{T} thresholds of the jets, are $0.023 \pm 0.003(\mathrm{stat.}) \pm 0.005(\mathrm{sys.})$, for jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $0.022 \pm 0.004(\mathrm{stat.}) \pm 0.005(\mathrm{sys.})$, for jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ [9].

2˙4. *$t\bar{t}$ production in association with additional bosons.* – A measurement of the production of $t\bar{t}$ in association with a vector boson ($t\bar{t} + V$) is a key test of the validity of the SM at the TeV scale. CMS performs the measurement of $\sigma(t\bar{t} + V)$ [10] using the full 7 TeV dataset. Two complementary analyses are employed: one based on the trilepton signatures produced in $t\bar{t} + Z$ decays and one based on same-sign dilepton signatures produced by $t\bar{t} + Z$ signatures where $V = W$ or Z. The measured cross sections are $\sigma_{t\bar{t}+Z} = 0.28^{+0.14}_{-0.11}(\mathrm{stat.})^{+0.06}_{-0.03}(\mathrm{syst.})$ and $\sigma_{t\bar{t}+V} = 0.43^{+0.17}_{-0.15}(\mathrm{stat.})^{+0.09}_{-0.07}(\mathrm{syst.})$. These results are compatible with the NLO prediction of the SM.

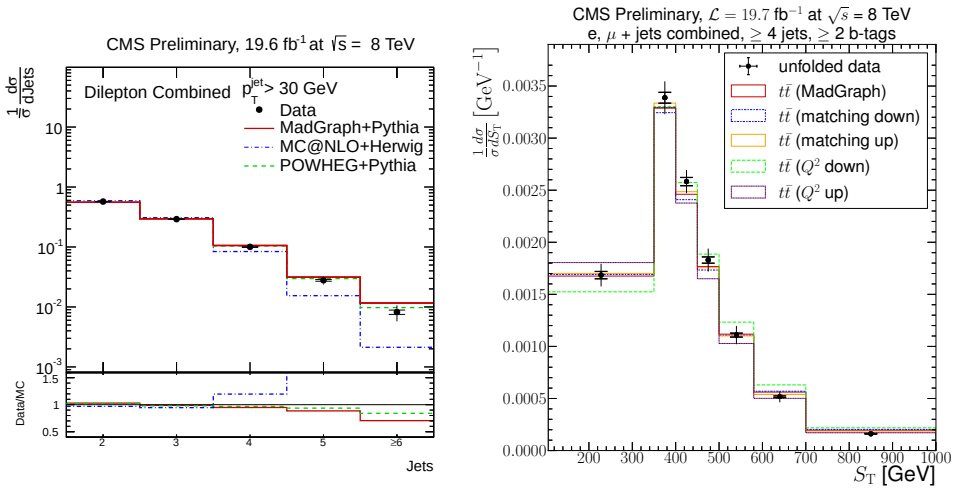

Fig. 3. – $t\bar{t}$ production cross section as a function of jet multiplicity (left) and S_T (right), defined by the sum of the transverse momenta of all jets, missing transverse energy and the isolated lepton. The results are compared to predictions from MadGraph with varied renormalisation/hadronisation scales and jet-parton matching threshold.

The production cross section of $t\bar{t}$ associated with a photon has been recently measured at $\sqrt{s} = 8\,\text{TeV}$ [11]. The $t\bar{t} + \gamma$ measurement is performed in the μ+jets decay channel. Events are selected by requiring a photon with a transverse energy greater than 20 GeV and an angular distance between the photon and the b quark $\Delta R(\gamma, b) > 0.1$, in addition to the $t\bar{t}$ selection. Prompt photons are estimated from a binned maximum-likelihood fit to the charged hadron isolation, defined as the sum of the energy of all charged hadronic candidates within $\Delta R < 0.4$. The transverse energy of the selected photons and the result of the template fit are shown in fig. 5. The normalised cross section is measured to be $\sigma(t\bar{t} + \gamma)/\sigma(t\bar{t}) = (1.07 \pm 0.07(\text{stat}) \pm 0.27(\text{syst})) \cdot 10^{-2}$.

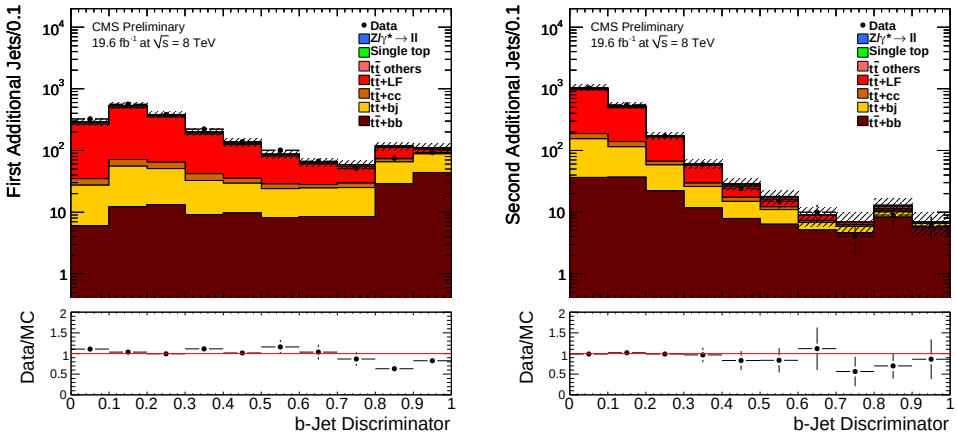

Fig. 4. – Distribution of the b-jet discriminator for the first (left) and second (right) additional jets in events with particle-level jets with a minimum p_T of 20 GeV after the final selection.

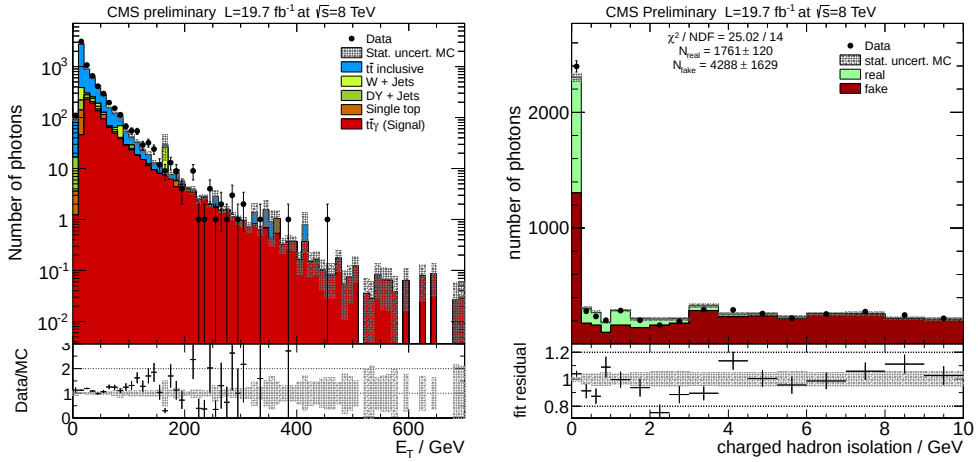

Fig. 5. – Photon transverse energy of selected candidates after all selection requirements (left) and binned template fit to charged hadron isolation (right).

3. – Single top production

Single top processes are a direct probe of the Wtb coupling and of V_{tb} element of the CKM matrix. They represent an important background for Higgs searches in associated production $W/ZH \to qqbb$. Moreover, they are sensitive to many models of new physics affecting the Wtb vertex like Flavor Changing Neutral Currents (FCNC) and anomalous couplings; or involving new particles, like W' or charged Higgs bosons. In this section measurements of the inclusive cross section of the t-channel and tW associated production are presented, as well as the first measurement of the s-channel production.

3˙1. *t-channel.* – The cross section measurement using data at 8 TeV has been performed studying the muon channel only [12]. Events are identified by the presence of an isolated lepton, a central b-tagged jet and a forward light jet. The analysis strategy is based on a fit to the pseudorapidity distribution of the recoil jet. The measured cross section results $\sigma = 80.1 \pm 13.0$ pb, from which a value of $|Vtb| = 0.96 \pm 0.08(\text{exp.}) \pm 0.02(\text{th.})$ (or constrained $|Vtb| > 0.81$ at 95% CL) is extracted.

The t-channel process in pp collisions is characterised by the asymmetry in the production of top quarks and antiquarks, as the density of u quarks is almost twice the density of d quarks. The measurement of this asymmetry can help to constrain the parton distribution functions of the proton. The analysis is also performed by a fit to the pseudorapidity distribution of the recoil jet, in this case separated by lepton charge (which reflects the top quark charge). The distribution of $|\eta_{j'}|$ for μ^+ is shown in fig. 6, left. The ratio $\sigma(t)/\sigma(\bar{t})$ is measured combining the electron and muon channels and yields $R = 1.76 \pm 0.14(\text{stat}) \pm 0.21(\text{syst})$ [13], in agreement with the SM prediction, see fig. 6, right.

3˙2. *tW-channel.* – CMS achieved the first observation of the associated production of a single top quark and W boson in pp collisions at 8 TeV [14]. The measurement is performed using events with two leptons and a jet originated from a b quark. A multivariate analysis based on kinematic properties is applied to separate the signal from the $t\bar{t}$ background. The signal is observed at a significance of 6.0 standard deviation

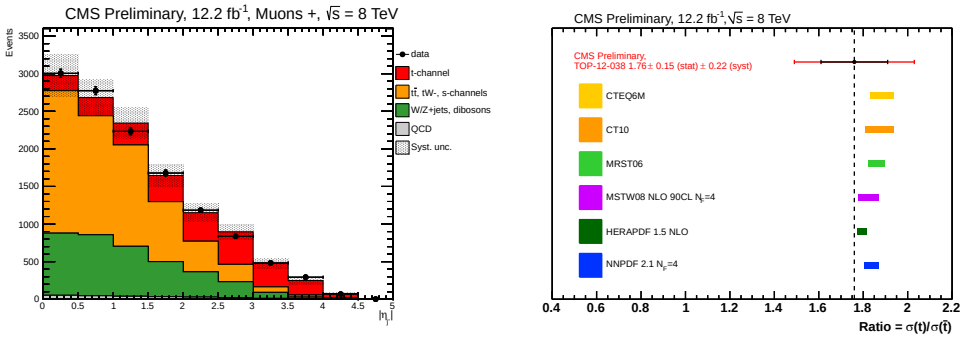

Fig. 6. – Distribution of $\eta_{j'}$ for muons in the signal sample (left) and measured ratio of t-channel single top and single antitop cross sections, compared with the values obtained using different sets of parton density functions. The uncertainties include the factorisation and renormalisation scales and top mass uncertainties (right).

above the background-only hypothesis. The corresponding measured cross section value is: $\sigma_{tW} = 23.4 \pm 5.4\,\text{pb}$, from which a value of $|V_{tb}| = 1.03 \pm 0.12(\text{exp.}) \pm 0.04(\text{th.})$ (or $|Vtb| > 0.78$ at 95% CL) can be extracted.

3˙3. *s-channel*. – A search for single top quark production in the s-channel has been performed using the data collected at 8 TeV. The topology of these events is characterised by the presence of one isolated lepton and two b quarks, one from the top-quark decay and one recoiling against the top quark. The signal is extracted by performing a maximum-likelihood fit to the distribution of a multivariate discriminant defined to separate the expected signal contribution from the background processes. This analysis leads to an upper limit on the cross section times branching ratio of 11.5 pb at 95% CL [15].

A summary of the results, including those for $\sqrt{s} = 7\,\text{TeV}$, is shown in fig. 7.

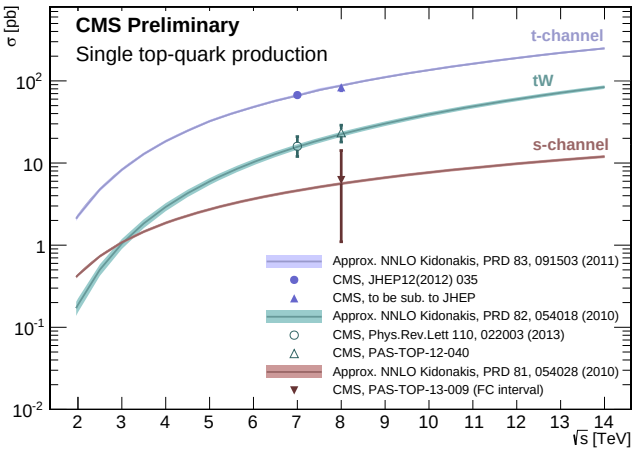

Fig. 7. – Summary of single top cross section measurements by CMS, as function of centre-of-mass energy.

4. – Conclusions

Top quark measurements provide important information about the production process as described in QCD, as well as sensitivity to possible new physics. In the last years, the LHC has become a real "top factory", so the uncertainty of many results is dominated by the systematic ones. The large statistics collected allowed, for instance, to perform precise inclusive and differential $t\bar{t}$ cross section measurements. In the sector of single top quark production, the t-channel cross section is measured at all energies, tW processes have been observed at 8 TeV and an upper limit on the s-channel cross section has been set. All results so far are consistent with the expectations of the SM.

REFERENCES

[1] CMS Collaboration, *JINST*, **3** (2008) S08004.
[2] The CMS top quark physics results public webpage, `https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP`.
[3] CMS Collaboration, *JHEP*, **02** (2014) 024.
[4] CMS Collaboration, Cross section measurement in the l+jets channel at 8 TeV, CMS-PAS-TOP-12-006 (2012).
[5] CMS Collaboration, Measurement of the differential $t\bar{t}$ cross section in the dilepton channel at 8 TeV, CMS-PAS-TOP-12-028 (2013).
[6] CMS Collaboration, Measurement of the differential $t\bar{t}$ cross section in the lepton+jets channel at 8 TeV, CMS-PAS-TOP-12-027 (2013).
[7] CMS Collaboration, Measurement of the Jet Multiplicity in Di-leptonic Top Quark Pair events at 8 TeV, CMS-PAS-TOP-12-041 (2013).
[8] CMS Collaboration, Measurement of missing transverse energy and other event-level observables in top pair events at $\sqrt{s} = 8$ TeV, CMS-PAS-TOP-12-042 (2013).
[9] CMS Collaboration, Measurement of Cross Section Ratio $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ in pp Collisions at 8 TeV, CMS-PAS-TOP-13-010 (2013).
[10] CMS Collaboration, *Phys. Rev. Lett.*, **110** (2013) 172002.
[11] CMS Collaboration, Measurement of the top-quark pair + photon production cross section in the muon+jets channel at 8 TeV, CMS-PAS-TOP-13-011 (2013).
[12] CMS Collaboration, Measurement of the single-top t-channel cross section in pp collisions at centre-of-mass energy of 8 TeV, CMS-PAS-TOP-12-011 (2012).
[13] CMS Collaboration, Measurement of the top/antitop production ratio in single top t-channel production at 8 TeV, CMS-PAS-TOP-12-038 (2013).
[14] CMS Collaboration, Observation of the associated production of a single top quark and a W boson in pp collisions at $\sqrt{s} = 8$ TeV, CMS-PAS-TOP-12-040, arXiv:1401.2942.
[15] CMS Collaboration, Search for single-top production in the s channel at 8 TeV, CMS-PAS-TOP-13-009 (2013).