

Results on top-quark physics and top-quark-like signatures by CMS

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Abstract. This report reviews the results obtained by the CMS Collaboration on top quark physics, focusing on the latest ones based on p–p collisions provided by the LHC at $\sqrt{s}=13$ TeV during Run II. It covers measurements of single-top, top quark pairs and associated productions as well as measurements of top quark properties. Finally several beyond the standard model searches involving top quark in the final states are presented, such as searches for supersymmetry in the third generation, heavy resonances decaying into a top quark pair, or dark matter produced in association to a single-top or a top quark pair.

1. Introduction

The study of the top quark is a domain in itself within the field of the particle physics. Latest quark being discovered by the Tevatron experiments at Fermilab in 1995, the top quark has been intensively studied at the LHC. In this note we will mainly focus on the results obtained by the CMS collaboration [1]. However, when available, we will present as well results obtained by combining measurements performed by ATLAS [2] and CMS collaborations.

It is the heaviest elementary particle ever discovered; its mass has been measured with an excellent accuracy to 173.34 ± 0.27 (stat.) ± 0.71 (syst.) GeV [3] (world combination) . The existence of the Brout-Englert-Higgs mechanism revealed by the discovery of the Higgs boson [4, 5] induces a strong interplay between Higgs and top quark physics as the Yukawa coupling of the latter is large. Quadratic divergences appear in the computation of the Higgs boson mass and are dominated by top quark loop contributions. This induces a fine-tuning in the renormalisation procedure often referred as the naturalness problem. The top quark has a very short lifetime, about 10^{-25} seconds, which is lower by one order of magnitude than the typical hadronization timescale and by four orders of magnitude than the characteristic spin decorrelation time. This has two important consequences: firstly no strong bound states made of top quark exists and secondly the top quark will decay before hadronizing, transmitting its spin information to its product decays.

Top quarks decay via the electroweak interaction into a W boson and a bottom quark with a branching ratio (BR) of about 1. Tiny other top quark contributions in the CKM matrix are studied by dedicated analysis. The study of the top quark decays allows to test the V-A structure of the electroweak interaction leading to studies such as the W-helicity measurements [7]. As W bosons can decay either leptonically or hadronically, top quark physics can be studied via few final states, three for top quark pair production.



2. Production of top quarks

2.1. Top quark pair production

Many standard model (SM) processes can produce top quarks in the final state. The dominant one is the top quark pair production, $t\bar{t}$, which is dominated by gluon-gluon fusion at LHC (about 90% at 13 TeV). The cross-section of this strong interaction process is proportional to $(\alpha_S/m_{top})^2$ at the leading order of the perturbative theory where α_S is the strong coupling constant and m_{top} is the top quark mass. By consequence its measurement is a multi-purpose test. Comparisons of experimental measurements to the best theoretical calculations performed at next-to-next-to-leading order allow to test the perturbative QCD. Both experimental and theoretical uncertainties have reached a threshold of 2-3% [8, 9]. Moreover cross-section measurements can be reinterpreted in term of constraints either on α_S or on the top quark mass.

Measurements have been performed at all center-of-mass energies delivered by the LHC in several final states by both ATLAS and CMS experiments. These results are summarized in the left plot of the Figure 2.1. The right plot reports the latest measurements done at 13 TeV with their combination performed by the LHC Top Working Group. All reported measurements are compatible with the theoretical predictions. With the high integrated luminosity recorded, those measurements are not dominated by statistic uncertainties but by the systematics ones. The channel with the best accuracy is thus the dileptonic final state with one electron and one muon. Although the branching ratio is small, about 2%, the channel is pure and do not suffer from backgrounds uncertainties, Drell-Yann contributions being heavily suppressed by the requirement of opposite lepton flavor. While the first cross-section measurements were based on counting experiments, the application of profile likelihood ratio methods relying on a categorization of the events have considerably helped to reduce the systematic uncertainties. Indeed by describing the main uncertainties such as the jet energy scale in term of nuisance parameters into the fit, the choice of appropriate categories or distributions led to a reduction of the sensitivity to those parameters. A categorization based on the jet multiplicity and the jet p_T spectrum was used in the 8 TeV measurement [8].

The cross-section measurements were used for several reinterpretations such as an accurate measurement of α_S leading to a measured value of $\alpha_S(m_Z) = 0.1151 \pm_{0.0027}^{0.0028}$ [10]. The dependence of the cross-section as function of the top quark mass has been parametrized from the 7 and 8 TeV measurements as following [8]:

$$\sigma_{t\bar{t}}(7\text{TeV}, m_t^{\text{MC}}) = \exp \left[-0.1718 (m_t^{\text{MC}}/\text{GeV} - 178.5) \right] + 170.9 \text{ pb} \quad (1)$$

$$\sigma_{t\bar{t}}(8\text{TeV}, m_t^{\text{MC}}) = \exp \left[-0.1603 (m_t^{\text{MC}}/\text{GeV} - 185.4) \right] + 237.0 \text{ pb} \quad (2)$$

Similar results have been obtained and reported with 13 TeV measurements [11].

2.2. Single top quark production

Top quarks can also be produced from weak interactions through three processes: t-channel, Wt-channel and s-channel. These processes have smaller cross-sections than the pair production mechanism as they involve the weak coupling constant and probe different parton density functions (pdf), in particular the anti-quark or b-quark ones. The cross-sections of these processes are proportional to $|V_{tb}|^2$ where V_{tb} is one of the element of the CKM matrix. The study of the single top production allows to probe the tWb vertex through studies of the top quark polarisation. Cross-sections have been measured at 7, 8 and 13 TeV and the measurements and their combinations performed by the LHC Top WG are summarized in Fig. 2.2. Beyond cross-section measurements several reinterpretations have been made. Thereby the ratio of the measurement in the t-channel for top and anti-top, identified from the charge of the lepton in

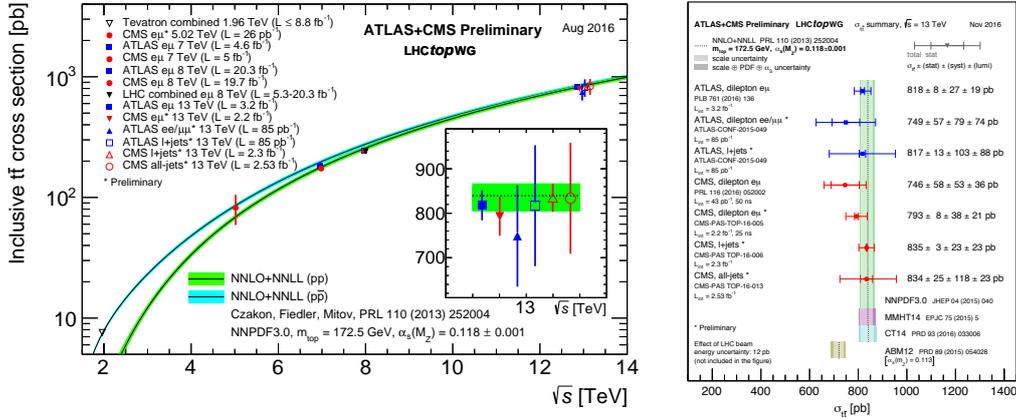


Figure 1. Left plot: Summary of LHC and Tevatron measurements of the top-pair production cross-section as a function of the centre-of-mass energy compared to the NNLO+NLL calculation [6]. The theory band represents uncertainties due to renormalisation and factorisation scale, parton density functions and the strong coupling. **Right plot:** Summary of measurements of the top-pair production cross-section at 13 TeV compared to the NNLO+NLL calculation [6].

the final state, has been used to constrain the relative pdf of up and down quarks in the proton [12]. As presented in Fig. 2.2, the measurement is in agreement with all sets of pdf used in this analysis. Moreover the single top cross-section measurements have been reinterpreted in term of value of $|f_{LV}V_{tb}|$ where f_{LV} is a parameter which encapsulates possible contributions from new physics and is equal to 1 for the SM. The results do not rely on any assumption on unitarity of the CKM matrix. Reported in Fig. 2.2, the results show no deviation to the SM prediction. As a comparison, another constraint on the CKM matrix element V_{tb} have been obtained by fitting the b-jet multiplicity in di-lepton events resulting in a bound of $V_{tb} > 0.955$ at 95% CL [13].

3. Differential cross-section measurements

Although inclusive cross-section measurements of the single top and $t\bar{t}$ productions already offer numerous possibilities for reinterpretation, the study of differential cross-sections provide new opportunities. They are based on unfolding techniques which correct the observed distributions for efficiency, acceptance and resolution effect. The unfolded distributions can then be directly compared to any predicted model. Thus the study of differential cross-sections allow to test and constrain the generator predictions. The Fig. 4 shows differential cross-sections at parton level [14] as function of $p_T(t\bar{t})$, $|y(t\bar{t})|$, $M(t\bar{t})$, and cross sections as a function of the number of additional jets compared to several generator chains. These studies are important for BSM searches where the top quark contribution is an important background as it increases the confidence into the generator chain used or define a domain of validity in case of discrepancies with the data. The study of the jet multiplicity allows to probe the whole simulation chain. The lower multiplicities are mainly sensitive to the Matrix Element description while the higher multiplicities are mainly sensitive to the parton shower description. As seen in Fig. 4, the predictions of $t\bar{t} + \geq 4$ jets could vary to up-to 50% depending on the generator chain while they agree at lower multiplicity. The measurement in data helps to decide which generators are able to correctly describe the physics of interest.

Measurement of different cross-sections can also be used to measure physical parameters or to constrain them. Thereby the measurement of the double differential cross-section of $m(t\bar{t})$ and $y(t\bar{t})$ [16] has been used to constrain the pdfs and especially to improve the gluon pdf at

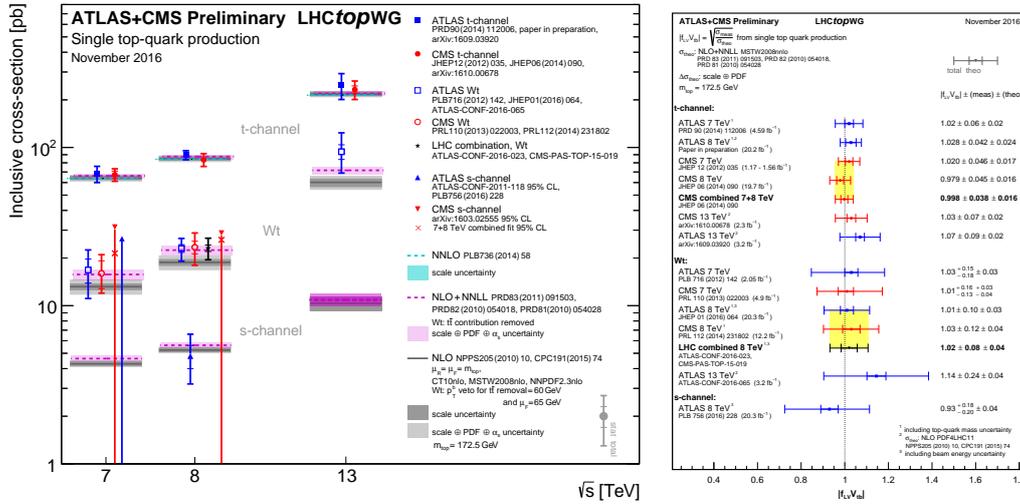


Figure 2. **Left plot:** Summary of ATLAS and CMS measurements of the single top production cross-sections in various channels as a function of the center of mass energy. The measurements are compared to theoretical calculations (NLO+NLL except for the t-channel: NNLO+NLL) [6]. **Right plot:** Summary of the ATLAS and CMS extractions of the CKM matrix element V_{tb} from single top quark measurements. The measurements below the line were made after the LHC combination that is shown in the upper part of the figure [6].

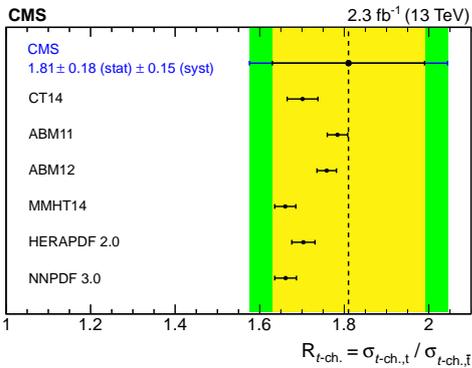


Figure 3. Comparison of the measured t and \bar{t} cross-section ratio in the t-channel (dotted line) with the prediction from different PDF sets. The error bars for the different PDF sets include the statistical uncertainty, the uncertainty due to the factorization and renormalization scales and the uncertainty in the top quark mass [12].

high x as presented in Fig. 3.

3.1. Associated production

Top quark pairs can be produced in association with electroweak bosons. The $t\bar{t}W$ and $t\bar{t}Z$ processes have been observed for the first time at LHC during run I [17] and are now measured at run II [18] with uncertainties equally shared between statistic and systematic uncertainties. The multi-leptons final states are studied in order to reduced the major backgrounds. While the requirement of two leptons compatible with the Z boson significantly improves the purity of the sample for the measurement of $t\bar{t}Z$, the selection of $t\bar{t}W$ rely on a multivariate approach based on kinematic variables such as the transverse missing momenta (\cancel{E}_T), the leading lepton or jet p_T . A categorization of the selected events based on (b-tagged) jets helps to reduce the systematic uncertainties. The latest measurements are:

$$\sigma_{t\bar{t}W} = 0.98 \pm_{0.22}^{0.23} \text{ (stat)} \pm_{0.18}^{0.22} \text{ (syst)} \text{ pb} \quad (3)$$

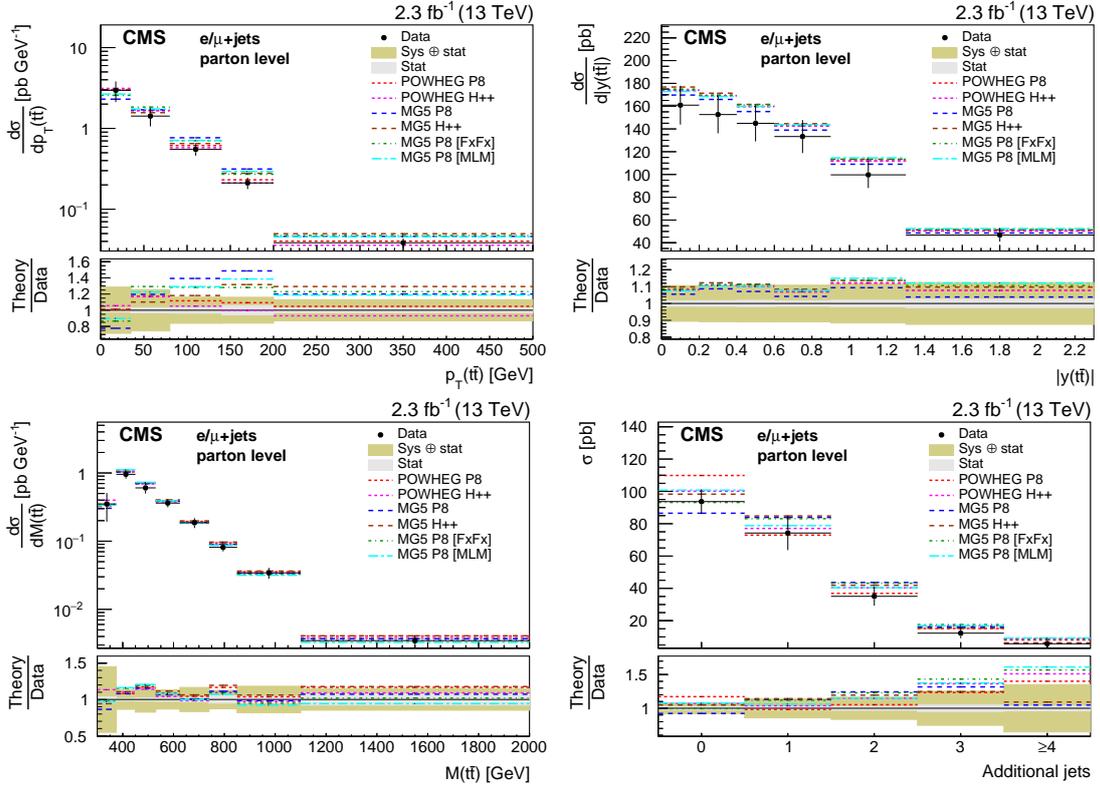


Figure 4. Differential cross sections at parton level as a function of $p_T(t\bar{t})$, $|y(t\bar{t})|$, $M(t\bar{t})$, and cross sections as a function of the number of additional jets compared to the predictions of POWHEG and MG5-MC@NLO (MG5) combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5-MC@NLO +PYTHIA8 MLM and MG5-MC@NLO +PYTHIA8 FxFx. The ratios of the various predictions to the measured cross sections are shown at the bottom of each panel together with the statistical and systematic uncertainties of the measurement [14].

$$\sigma_{t\bar{t}Z} = 0.70 \pm_{0.15}^{0.16} (\text{stat}) \pm_{0.12}^{0.14} (\text{syst}) \text{ pb} \quad (4)$$

The production of top quark pairs in association with a photon have also been studied. The physical process is different as the photon can be emitted by any charged particle including initial states radiations or decay products of the W bosons. Thus one should define a p_T threshold for the studied photons. The analysis strategy is based the measurement of the fraction $t\bar{t}$ events where an additional photon is observed. This ratio has been measured [19] to be $(5.2 \pm 1.1) \times 10^{-4}$ for photon with $p_T > 25$ GeV leading to a measurement of the fiducial $t\bar{t}\gamma$ cross-section of 127 ± 27 fb.

3.2. Rare processes

Top decays with Flavour Changing Neutral Current (FCNC) are suppressed by the GIM mechanism [15] within the SM and lead to rare processes currently not accessible at LHC with the available luminosity. Thus any observation of such decays would be a sign of new phenomena. Many BSM models predict an increase of the cross-section of these processes by many orders of magnitude. All possible decays have been studied: $t \rightarrow u/c + (\gamma/Z/g/H)$. The SM branching ratios (BR) range from 10^{-12} to 10^{-17} while they could be as large as $10^{-9} - 10^{-6}$

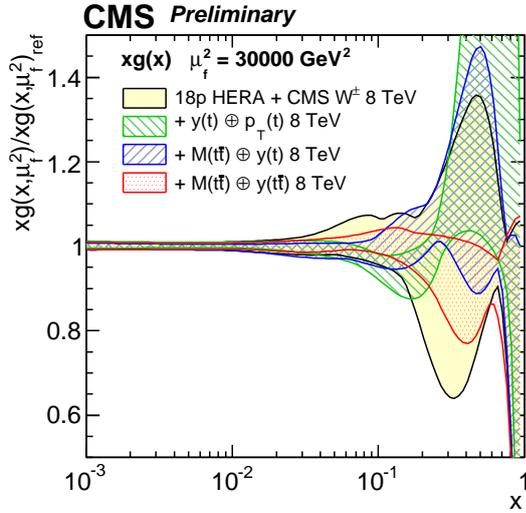


Figure 5. The gluon distributions at $\mu_f^2 = 30\,000\text{ GeV}^2$, as obtained in all variants of the PDF fit, normalized to the results from the fit using the DIS and W^\pm boson charge asymmetry data only. The total uncertainty of each distribution is shown by a shaded (or hatched) band [16].

in some BSM models. The studies have been made in single top production as well as in $t\bar{t}$. The analyses often rely on multivariate techniques to enhance the observability of tiny signals. A summary of the state of the art is reported in the Fig. 3.2. No excess has been found so far and the results were interpreted in term of limits which dominated by statistics and thus large improvements are expected in coming years.

Four top quark production is predicted by the SM but the cross-section is so tiny than it is outside the reach of the LHC at run II. However, many BSM processes predict an enhancement of the inclusive production of four top quarks in the final state such as in supersymmetric models. A generic search has been performed and has constrained the cross-section of this process. Using final states with one or two leptons, the analysis reported in [20] makes use of a Boosted Decision Tree (BDT) to reconstruct hadronic top quarks, a global event BDT to separate SM backgrounds from the signal as well as a categorization as function of the (b-tagged) jets multiplicity. The current limit is 10.2 times greater than the cross-section predicted within the SM.

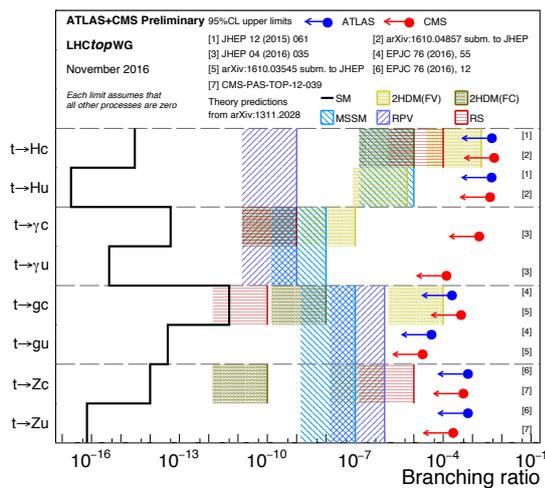


Figure 6. Summary of the current 95% confidence level observed limits on the branching ratios of the top quark decays via flavour changing neutral currents to a quark and a neutral boson $t \rightarrow Xq$ ($X=g, Z, \gamma$ or H ; $q=u$ or c) by the ATLAS and CMS Collaborations compared to several new physics models.

4. Properties of the top quark

The most well-known and studied property of the top quark is its mass. As highlighted in the introduction, its importance is related to the interplay with the Higgs mechanism. The accuracy

reached at the LHC is beyond the original projections thanks to the developments of advanced analysis techniques and a good control of the main systematics. The largest ones such as the jet energy correction were reduced by the use of in-situ measurements in some analyses. A broad variety of techniques have been developed. Their combination does not only improve the combined results but also gives confidence in the measured value as they are all in agreement. CMS has released few month ago a note [21] where alternative methods have been presented and combined. Combined with previous published CMS measurements, the measured value is 172.43 ± 0.13 (stat) ± 0.46 (syst) GeV.

Less studies, the top quark width has been directly or indirectly measured by few dedicated analyses. A recent paper [22] has studied the invariant mass of the lepton plus closest b-tagged jet. This observable should have a kinematic endpoint with a maximal value defined by $M_{lb}^{max} = \sqrt{m_t^2 - m_W^2}$. Contributions beyond that value are due both the top quark width as well as the experimental resolution and combinatoric effects. Thus this observable is sensitive to the top quark width. A measurement has been performed in the dileptonic channel, setting the following bounds: $0.6 \leq \Gamma_t \leq 2.4$ GeV.

A large program of the top quark physics is dedicated of the measurements of the charge asymmetries and the spin correlation but will not be mentioned here.

5. Search of new physics with top quarks in the final states

5.1. $t\bar{t}$ resonances

Many BSM models predict new particles that could decay into a top quark pair. The nature and spin of the resonance varies accross the models. Spin 1 bosons such as Z' should appear as a peak above the $t\bar{t}$ continuum in the invariant mass spectrum of the $t\bar{t}$ system. The searches are often decoupled into two regimes depending on the invariant mass of the resonances and thus on the kinematic regime of the top quark pair. While at low mass the events will appear in resolved topology where all jets are visible, at high mass the boost is such that then angles are reduced and the jets would merge. The search of Z' [24] with 13 TeV data [24] has reveal no excess and limits have been set on topcolor Z' with several width hypotheses and on Kaluza-Klein excitations of a gluon. With a luminosity of $2.3 fb^{-1}$, the sensitivity was equivalent to the one obtained at Run I. The 95% CL limits can reach 4 TeV in the case of Z' with $\frac{\Gamma}{M} = 0.3$.

5.2. Supersymmetric processes with top in the final states

Many supersymmetric (SUSY) processes involve top quark in the final state. The most obvious case is the production of supersymmetric top quark partners often referred as stop. Among the possible decay chain for the stop pair production, the decay into a top quark and the lightest neutralino has been intensively investigated. Top quarks could also be produced in the decay chain of gluino production. In the case of hadronic decay of the top quark, dedicated techniques can be applied. There are a variety of top-tagging techniques on the market but the basic principle remains almost the same. It uses a jet algorithm with a large parameter, sufficiently large to collect the three-body decay of the top quark. Then to discriminate those fat jets from the other jets, one needs to probe their substructure. Declustering techniques are applied associated with pruning/trimming techniques in order to remove pile-up dependencies. The invariant mass of the jet is used to select the jet as well as consideration on the sub-jets. Such techniques have been used for SUSY searches leading to large improvement in term of sensitivity at high sparticle masses. Searches in the hadronic channel [25, 26] using those techniques as set limits on stop mass up to 900 GeV with $12.9 fb^{-1}$ of p-p collisions at 13 TeV. Reinterpretations have also been done in the context the gluino pair productions with constrain on its mass going up to about 1750 GeV.

5.3. Top quark in association with dark matter candidates

The search of dark matter (DM) at LHC cover many possible final states. The strategy has been established in such a way that it should be possible to more easily reinterpret the constraints or observations made at LHC in term of specific models. Many analyses are looking for final states with DM+X where X could be a jet, a photon which would boost the system and make a clear signature. One of the considered signature is the production of DM in association with a top quark. Two scenarii were considered, one via the resonant production of a colored scalar that couples to a top quark and a fermionic DM candidate, the second one with FCNC production of a top quark and a new vector boson which could decay into a DM candidate pair. The experimental signature is the presence of a top quark in association with a large \cancel{E}_T . Analysis [27] in the hadronic final states has been established with 13 TeV data and put constraints on both considered models.

The production of a pair of DM candidate in association of the top quark pair has also been considered. Such model considered the existence of (pseudo-)scalar mediator between the top quark and the DM sector. A search has been setup looking for signature with 0 or 1 lepton in the final state with 13 TeV data [28]. The selection rely on strong requirement on \cancel{E}_T as well as a specific reconstruction of the top quark. Limits were obtained by fitting \cancel{E}_T distributions.

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