IL NUOVO CIMENTO **43 C** (2020) 30
DOI 10.1393/ncc/i2020-20030-7

COLLOQUIA: IFAE 2019

Single top quark measurements with the CMS experiment

A. DE IORIO([1])([2])(*) on behalf of the CMS COLLABORATION

([1]) *Dipartimento di Fisica, Università degli Studi di Napoli Federico II - Napoli, Italy*
([2]) *INFN, Sezione di Napoli - Napoli, Italy*

received 8 June 2020

Summary. — Single top quarks are produced at the Large Hadron Collider in electroweak processes via charged current interaction. This channel is very sensible to new physics signals, like anomalous couplings or flavour changing neutral current, due to the presence of an electroweak vertex. The latest results obtained with the data collected by the CMS experiment (CMS COLLABORATION, *JINST*, **3** (2008) S08004) in 2015–2018 at $\sqrt{s} = 13\,\text{TeV}$ at the Large Hadron Collider, studying both inclusive and differential cross sections, allow to precisely probe the structure of the interaction vertex and to search for deviations from the Standard Model predictions.

1. – Introduction

The Large Hadron Collider (LHC) is the largest top factory. The top quark is the $Q = 2/3$, $t_3 = +1/2$ member of the weak-isospin doublet containing the bottom quark. Its phenomenology is driven by its large mass. Being heavier than a W boson, it is the only quark that decays weakly, *i.e.*, into a real W boson and a d-type quark, predominantly b quarks. Therefore, it has a very short lifetime and it decays before hadronisation can occur. In addition, it is the only quark whose Yukawa coupling to the Higgs boson is of the order of unity. For these reasons the top quark plays a special role in the Standard Model (SM) and in many extensions thereof. Its phenomenology provides a unique laboratory where our understanding of the strong interactions, both in the perturbative and non-perturbative regimes, can be tested. In addition, the nature of the V-A electroweak interaction at the tWb vertex means that only left-handed quarks are expected at this vertex. Thus, top quark decay products retain memory of the top quark spin orientation in their angular distributions. This turns the top quark into a powerful probe of the structure of the electroweak tWb vertex. An accurate knowledge of its properties (mass, couplings, production cross section, decay branching ratios, etc.) can bring key information on fundamental interactions at the electroweak breaking scale and beyond.

(*) E-mail: agostino.deiorio@na.infn.it

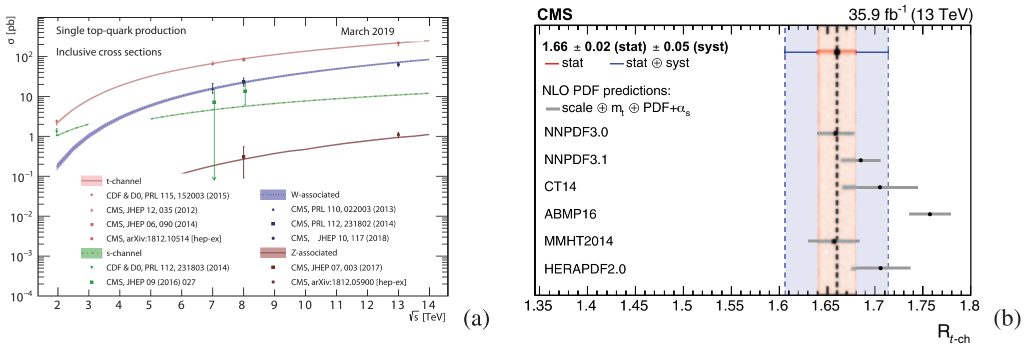

Fig. 1. – Single top quark cross section summary of CMS measurements compared to the theoretical calculations for t-channel, s-channel, and W-associated production; Tevatron measurements are also shown (a). Comparison of the measured $R_{t\text{-ch}}$ (central dashed line) with the next-to-leading order (NLO) predictions from different PDF sets (b) [1].

2. – Single top quark cross section

The single top quark can be produced via four different channels: t-channel, s-channel, tW associate production and tZ associate production. Since its discovery at Tevatron in 1994, the cross sections of these processes have been measured at the center-of-mass energy of 1.91 TeV at Tevatron and at 7, 8, and 13 TeV at LHC. Figure 1(a) shows a summary of the measurements performed by the CMS Collaboration compared to the theoretical predictions of the SM. All the measured values are in good agreement with the SM prediction.

In the t-channel, it is possible to perform a measurement of the cross section for the production of a top quark and of an anti-top quark by selecting the charge of the lepton coming from the W boson decay. The most recent measurement [1] performed by the CMS Collaboration found $\sigma_{\mathrm{t}}^{t\text{-ch.}} = 136 \pm 1 \pm 22$ pb and $\sigma_{\bar{\mathrm{t}}}^{t\text{-ch.}} = 82 \pm 1 \pm 14$ pb for the cross sections, and $R_{t\text{-ch.}} = 1.66 \pm 0.02 \pm 0.05$ for the ratio between them. The ratio of the cross sections of these two processes provides insight into the inner structure of the proton as described by the parton distribution functions (PDFs). Figure 1(b) shows the comparison between this measurement and the prediction of different PDFs sets available for LHC.

The t-channel process is particularly interesting for the measurement of the $|V_{tb}|$ CKM matrix element because of the strong dependence of the cross section on this parameter. The last measurement at 13 TeV [1] found $|V_{tb}| = 1.00 \pm 0.08(\mathrm{exp}) \pm 0.02(\mathrm{theory})$. The combination of the measurements at 7 and 8 TeV made by the ATLAS and CMS Collaborations [2] found $|V_{tb}| = 1.02 \pm 0.04(\mathrm{exp}) \pm 0.02(\mathrm{theory})$. The two measurements are in agreement between them and with the SM prediction.

3. – Top quark mass

The top physics is driven by the large mass of the top quark so it is of fundamental importance to measure this quantity with a high precision and in as many channels as possible. The last measurement performed in the single top t-channel by the CMS Collaboration at 8 TeV [3] gave $m_{\mathrm{t}} = 172.95 \pm 0.77^{+0.97}_{-0.93}$ GeV.

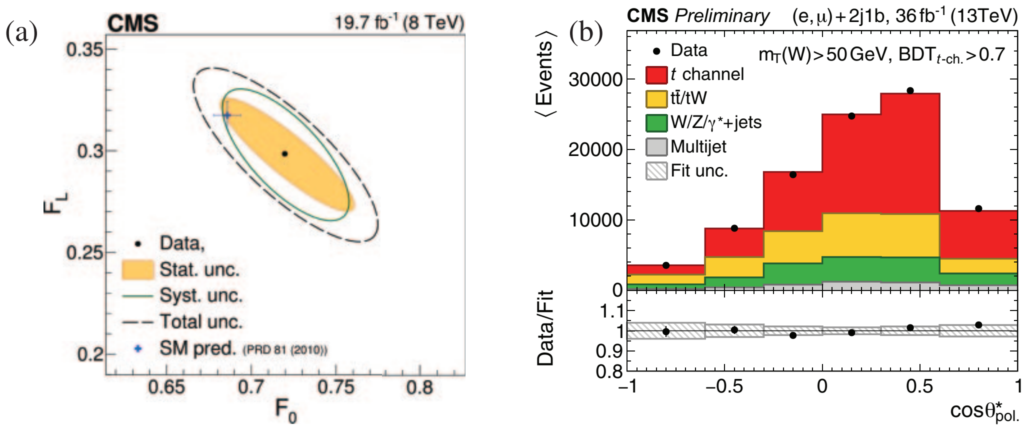

Fig. 2. – Combined results from the muon+jets and electron+jets events for the left-handed and longitudinal W boson helicity fractions, compared with the SM predictions (a) [4]. Distributions of the cosine of the top quark polarisation angle (b) [5].

4. – W boson helicity

Because of its high mass, the top quark decays before hadronisation and its spin information is accessible through its decay products. The polarization of the W bosons from top quark decays is sensitive to non-SM tWb couplings. The W boson can be produced with left-handed, longitudinal, or right-handed helicity; the relation $\Gamma(t \to Wb) = \Gamma_L + \Gamma_0 + \Gamma_R$ holds for the corresponding partial widths of the top quark decay. Hence, the W boson helicity fractions defined as $F_i = \frac{\Gamma}{\Gamma i}$, where $i = L, 0$, or R, fulfil the condition $\sum F_i = 1$. The helicity angle θ^* is defined as the angle between the W boson momentum in the top quark rest frame and the momentum of the down-type decay fermion in the rest frame of the W boson. The probability distribution function of $\cos\theta^*$ contains contributions from all W boson helicity fractions,

$$(1) \qquad \frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta^*_\ell} = \frac{3}{8}(1-\cos\theta^*_\ell)^2 F_L + \frac{3}{4}\sin^2\theta^*_\ell F_0 + \frac{3}{8}(1+\cos\theta^*_\ell)^2 F_R.$$

The last measurement [4] found $F_L = 0.298 \pm 0.028 \pm 0.032$, $F_0 = 0.720 \pm 0.039 \pm 0.037$, and $F_R = -0.018 \pm 0.019 \pm 0.011$ in agreement with the SM prediction, as shown in fig. 2(a).

5. – Single top quark polarisation

A powerful observable to investigate the coupling structure in the t-channel production is given by the top quark polarisation angle $\theta^*_{\text{pol.}}$, defined by

$$(2) \qquad \cos\theta^*_{\text{pol.}} = \frac{\vec{p}_{\text{q'}}^{\,(\text{top})} \cdot \vec{p}_\ell^{\,(\text{top})}}{|\vec{p}_{\text{q'}}^{\,(\text{top})}| \cdot |\vec{p}_\ell^{\,(\text{top})}|},$$

where the momenta of the charged lepton, ℓ, and the spectator quark, q', are calculated in the top quark rest frame.

The normalised differential cross section as a function of $\cos\theta^*_{\mathrm{pol.}}$ at the parton level is related to the top quark polarisation, P, as

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*_{\mathrm{pol.}}} = \frac{1}{2}(1 + P_{\mathrm{t}}^{(\vec{s})}\alpha_\ell \cos\theta^*_\ell) = \left(\frac{1}{2} + A_\ell \cos\theta^*_{\mathrm{pol.}}\right), \tag{3}$$

where A_ℓ denotes the spin asymmetry and α_ℓ the so-called spin-analysing power of the charged lepton from the top quark decay. Figure 2(b) shows the distribution of the cosine of the top quark polarisation angle. The spin asymmetry and/or polarisation has been measured at 13 TeV [5] and the result is $A_{e/\mu} = 0.439 \pm 0.032(\mathrm{stat}) \pm 0.053(\mathrm{syst})$.

6. – Rare single top quark production

The large number of high-energy collisions recorded to date allows the probing of very rare standard model processes. One such process is electroweak production of a single top quark in association with a Z boson and a quark, $pp \to tZq$. This process is sensitive to a multitude of SM interactions described via the WWZ triple-gauge coupling, the ttZ and tbW couplings, and the $bW \to tZ$ scattering amplitude. The CMS Collaboration reports the first observation of this process by measuring its cross section: $\sigma = 111 \pm 13(\mathrm{stat})^{+11}_{-9}(\mathrm{syst})$ fb [6].

The study of top quark production in association with a photon is an important test of the SM description of top quark interactions with gauge bosons, and plays an important role in the search for physics beyond the SM. The cross section for single top quark production in association with a photon is sensitive to the top quark charge, and to its electric and magnetic dipole moments. The CMS Collaboration reports the first evidence of this process [7]: the measured product of the cross section and branching fraction is $\mathcal{B}(t \to \mu\nu\mathrm{b})\sigma(t\gamma j) = 115 \pm 17^{+33}_{-27}$ fb, which is consistent with the SM prediction.

7. – Flavour changing neutral current processes

Flavour-changing neutral currents (FCNC) are absent at lowest order in the SM, and are significantly suppressed through the Glashow-Iliopoulos-Maiani mechanism at higher orders.

A search for FCNC involving a top quark and a Z boson is presented. The analysis uses the 2016 proton collision data collected by the CMS experiment at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}. The search focuses on single top quark and top quark pair FCNC interactions observable in three lepton final states, where the FCNC interaction happens at the production or at the top quark decay. No significant deviation is observed from the predicted background [8], as reported in fig. 3(a). Observed (expected) upper limits at 95% confidence level are set on the branching fractions of top quark decays: $\mathcal{B}(t \to uZ) < 0.024\%$ (0.015%) and $\mathcal{B}(t \to cZ) < 0.045\%$ (0.037%), assuming one non-vanishing coupling at a time.

The CMS Collaboration used single top quark events produced in the t-channel to search for top quark FCNC interactions. In particular, the analysis focused on the couplings of a top quark with a u or c quark via a gluon, tug and tcg, respectively. The 95% CL upper limits on coupling strengths are $|\kappa_{tug}|/\Lambda < 4.1 \times 10^{-3}\,\mathrm{TeV}^{-1}$ and $|\kappa_{tug}|/\Lambda < 1.8 \times^{-2}\,\mathrm{TeV}^{-1}$, where Λ is the scale for new physics, and correspond to upper limits on the branching fractions of 2.0×10^{-5} and 4.1×10^{-4} for the decays $t \to ug$ and

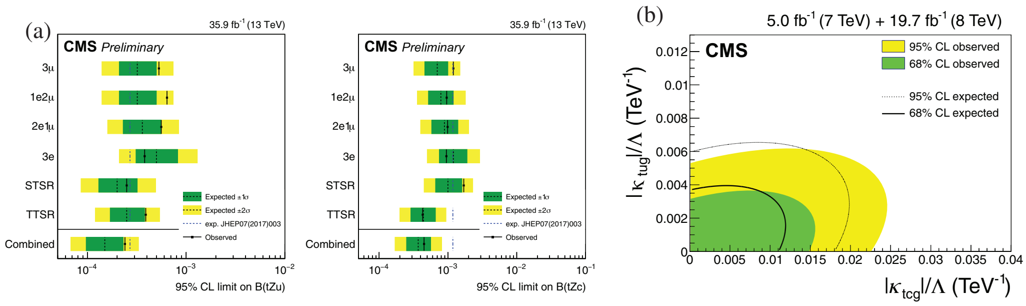

Fig. 3. – Exclusion limits at 95% CL for each leptonic channel and signal region on the FCNC tZu (left) and tZc (right) branching fractions considering one non-vanishing coupling at a time (a) [9]. Combined $\sqrt{s} = 7$ and 8 TeV observed and expected limits for the 68% and 95% CL on the $|\kappa_{tug}|/\Lambda$ and $|\kappa_{tcg}|/\Lambda$ couplings (b) [9].

$t \to cg$, respectively [9]. Figure 3(b) shows the combined $\sqrt{s} = 7$ and 8 TeV observed and expected limits for the 68% and 95% CL on the $|\kappa_{tug}|/\Lambda$ and $|\kappa_{tcg}|/\Lambda$ couplings.

8. – Conclusions

The top quark discovery at the Tevatron and the measurements of many properties of the top quark gave a strong confirmation of the SM of particle physics. The large amount of data collected by the CMS experiment allows the measurement of rare processes to test the SM predictions. Many Beyond SM (BSM) scenarios can also be tested with differential and multi-differential measurements. No deviations from the SM predictions are observed but the top quark sector is one of the most interesting for BSM manifestation.

REFERENCES

[1] CMS Collaboration (Sirunyan A. M. *et al.*), *Measurement of the single top quark and antiquark production cross sections in the t-channel and their ratio in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, arXiv:1812.10514 [hep-ex].
[2] ATLAS and CMS Collaborations (Aaboud M. *et al.*), *JHEP*, **05** (2019) 088, arXiv:1902.07158 [hep-ex].
[3] CMS Collaboration (Sirunyan A. M. *et al.*), *Eur. Phys. J. C*, **77** (2017) 354, arXiv:1703.02530 [hep-ex].
[4] CMS Collaboration (Khachatryan V. *et al.*), *JHEP*, **01** (2015) 053, arXiv:1410.1154 [hep-ex].
[5] CMS Collaboration (Sirunyan A. M. *et al.*), *Measurement of differential cross sections and charge ratios for t-channel single top quark production in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, arXiv:1907.08330 [hep-ex].
[6] CMS Collaboration (Sirunyan A. M. *et al.*), *Phys. Rev. Lett.*, **122** (2019) 132003, arXiv:1812.05900 [hep-ex].
[7] CMS Collaboration (Sirunyan A. M. *et al.*), *Phys. Rev. Lett.*, **121** (2018) 221802, arXiv:1808.02913 [hep-ex].
[8] CMS Collaboration, *Search for flavour changing neutral currents in top quark production and decays with three-lepton final state using the data collected at sqrt(s) = 13 TeV*, CMS-PAS-TOP-17-017.
[9] CMS Collaboration (Khachatryan V. *et al.*), *JHEP*, **02** (2017) 028, arXiv:1610.03545 [hep-ex].