Single top-quark production was discovered in 2009 by the CDF and D0 experiments at the Tevatron. At present running conditions, the LHC produces about 10k single top quarks per hour, opening therefore the possibility of studying the single top-quark physics with high precision.

The single top-quark production mechanism is an important tool for testing the Standard Model (SM) of particle physics. For example, cross-section measurements permit the direct determination of the $|V_{tb}|$ element of the CKM matrix. The structure of the $Wtb$ vertex including anomalous couplings can also be studied in detail. Moreover, the production cross-sections are sensitive to new particles, so any deviation from the predicted values would point to physics beyond the SM. In addition, single top-quark cross-section measurements can be used to constrain parton distribution functions sets (PDFs) and tune Monte Carlo (MC) generators. On top of that, single top-quark events are the dominant background in some Higgs and SUSY searches, so a proper understanding of the single top-quark physics is mandatory.

The top quark is produced singly through the electroweak interaction with the exchange of a virtual $W$ boson as in the $s$-channel and $t$-channel and in association with an on-shell $W$ boson in the $Wt$ production. Figure 1 shows the leading order (LO) Feynman diagrams for the three production modes. The theoretical cross-sections are calculated at next-to-leading order (NLO) for the $t$-channel and NLO involving next-to-next-to-leading order soft gluon corrections for the other channels. The cross-sections values calculated at different energies are:

- **8 TeV**: $\sigma_{s\text{-channel}} = 5.6 \pm 0.2 \text{ pb}$, $\sigma_{Wt} = 22.4 \pm 1.5 \text{ pb}$, $\sigma_{t\text{-channel}} = 87.7^{+3.4}_{-1.9} \text{ pb}$
- **13 TeV**: $\sigma_{s\text{-channel}} = 10.3 \pm 0.4 \text{ pb}$, $\sigma_{Wt} = 71.7 \pm 3.8 \text{ pb}$, $\sigma_{t\text{-channel}} = 217.0^{+9.1}_{-7.7} \text{ pb}$

where the theoretical uncertainty is the sum in quadrature of the scale and PDF uncertainties.

This summary focuses on the recent results obtained by the ATLAS and CMS Collaborations. It includes the evidence for $s$-channel production at $\sqrt{s} = 8$ TeV published by ATLAS, the LHC combination of the $Wt$ cross-section measurement at $\sqrt{s} = 8$ TeV as well as the $Wt$ cross-section measurement performed by ATLAS at $\sqrt{s} = 13$ TeV. The inclusive $t$-channel cross-section is measured by ATLAS and CMS at $\sqrt{s} = 13$ TeV. The fiducial and differential cross-sections are also measured at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV by ATLAS and CMS respectively. Top-quark polarisation in single top-quark events is also studied by both.
ATLAS$^{11}$ and CMS$^{12}$ at $\sqrt{s} = 8$ TeV and a search for the SM production of the single top-quark in association with a $Z$ boson at $\sqrt{s} = 8$ TeV is performed by CMS$^{13}$ only.

2 Cross-section measurement

Single top-quark production cross-sections have been measured in all different production channels by ATLAS and CMS. Although the strategy followed depends on the analysis, a common procedure still holds. First, a series of cuts are applied to select interesting events. These events are split in different regions: one enriched in signal events, called signal region; and other regions dominated by background events. The additional regions are called control regions if they are used to constrain the background rate and validation regions if they are used to validate the final results. Despite having a signal region, the ratio of signal over background events is usually quite low and a multi-variate analyses (MVA) such as Neural Network (NN) or Boosted Decision Trees (BDT) are needed to separate better the signal from the background. A likelihood fit to the data MVA discriminant is used to extract the cross-section value. The extraction of the $|V_{tb}|$ matrix element from single top-quark cross-section measurements is done using the relation $|f_{LV}V_{tb}|^2 = \sigma_{\text{obs.}} / \sigma_{\text{th.}}$ where obs. and th. stand for observed and theoretical cross-sections respectively, and $f_{LV}$ is a form factor that could be modulated by new physics. This equation assumes certain conditions: the $Wtb$ vertex interaction is an SM-like left-handed interaction and the CKM matrix elements $|V_{td}|$, $|V_{ts}|$ are negligible compared with $|V_{tb}|$. Assumptions on the number of quark families or unitarity of the CKM matrix are not required.

2.1 Evidence for the $s$-channel production mode

The $s$-channel is the most challenging single top-quark process at the LHC. Its experimental signature, as seen in Figure 1, is characterised by one isolated lepton, missing transverse momentum ($E_T^{\text{miss}}$) and two central jets which have been identified as containing $b$-hadrons ($b$-tagged jets). Due to the similar final topology, the main background events come from $t\bar{t}$, $W+$jets associated with heavy flavour and $t$-channel processes. Searches of the $s$-channel were previously reported by ATLAS and CMS$^{3}$ and the evidence was published by ATLAS using 20.3 fb$^{-1}$ of data collected at $\sqrt{s} = 8$ TeV. The analysis uses a signal region, a $W+$jets control region and a $t\bar{t}$ validation region. The cross-section is extracted from a maximum likelihood (ML) fit to the discriminant based on the matrix element (ME) method. The ME uses theoretical calculations to compute the signal probability per event. The measured cross-section is $\sigma = 4.8 \pm 0.8(\text{stat.}) \pm 1.6(\text{syst.})$ pb, consistent with the SM expectations and corresponding to an observed (expected) significance of 3.2 (3.9) standard deviations ($\sigma$). The extracted value of the $|f_{LV}V_{tb}|$ is $0.93^{+0.18}_{-0.20}$. The main systematic uncertainties come from the low statistics in MC samples, top-quark modelling and jet energy resolution (JER).
2.2 Measurement of the $Wt$ cross-section

The $Wt$ process represents the second highest single top-quark production cross-section at the LHC. The $Wt$ topology, shown in Figure 1, consists of two oppositely charged isolated leptons, $E_T^{\text{miss}}$ and a central $b$-tagged jet. Background events are composed mainly of dileptonic $t\bar{t}$ events. ATLAS and CMS published $Wt$ cross-section measurements at $\sqrt{s} = 8$ TeV. The LHC combination is extracted using a BLUE method, giving a value of $\sigma = 23.1 \pm 1.1(\text{stat.}) \pm 3.3(\text{syst.}) \pm 0.8(\text{lumi.})$ pb in agreement with the SM expectations. The corresponding $|f_{LV}V_{tb}|$ is computed to be $1.02 \pm 0.09$. The dominant systematic uncertainties come from the top-quark modelling. The $Wt$ cross-section has been also measured by ATLAS using $3.2 \, \text{fb}^{-1}$ of data at $\sqrt{s} = 13$ TeV. The strategy consists of two signal regions and one $t\bar{t}$ control region. A BDT is used to separate signal from $t\bar{t}$ background events. A ML fit to the discriminant in the signal and control region is applied. The measured $Wt$ cross-section results in $\sigma = 94 \pm 10(\text{stat.}) \pm 28(\text{syst.}) \pm 2(\text{lumi.})$ pb in agreement with the SM expectations. Dominant systematic uncertainties are mainly due to the jet energy scale (JES), JER, and modelling of the top-quark processes.

2.3 Measurement of the $t$-channel cross-section

The $t$-channel has the largest cross-section and nowadays it can start to be considered as the calibration channel in the single top-quark sector. The $t$-channel events, as seen in Figure 1, are selected if they have one isolated lepton, $E_T^{\text{miss}}$, one central $b$-tagged jet and one forward jet. The background events are mainly composed of $t\bar{t}$ and $Wt$+jets events.

Inclusive and differential cross-sections were published by CMS using $2.3 \, \text{fb}^{-1}$ of data at $\sqrt{s} = 13$ TeV. The inclusive cross-section is measured for the top quark and the top antiquark as well as the combination. The strategy includes one signal region, two $t\bar{t}$ control regions and one $W+$jets validation region. The measured total cross-section corresponds to $\sigma = 232 \pm 13(\text{stat.}) \pm 28(\text{syst.})$ pb in agreement with the SM expectations. Main systematic uncertainties come from the top-quark modelling. The $|f_{LV}V_{tb}|$ is calculated as $1.03 \pm 0.07(\text{exp.}) \pm 0.02(\text{th.})$. The ratio between the top quark and antiquark, $R_t = \sigma(t)/\sigma(\bar{t})$, is also measured as $1.81 \pm 0.18(\text{stat.}) \pm 0.15(\text{syst.})$. Results are compatible with a broad set of PDFs. The differential cross-section is measured as a function of the $p_T$ and rapidity ($|y|$). In order to enrich the samples with $t$-channel events a cut on the BDT is applied. Distributions are unfolded to parton level to correct for selection efficiencies and detector effects. The data is compatible with the MC predictions. Dominant uncertainties are low data statistics, top-quark modelling and JES.

ATLAS also performed the inclusive cross-section measurement at $\sqrt{s} = 13$ TeV. The strategy includes a signal region, a $t\bar{t}$ control region and a $W+$jets validation region. A NN is used to separate signal from background events. A ML fit to the NN discriminant is applied to extract the cross-sections of $\sigma_t = 156 \pm 5(\text{stat.}) \pm 27(\text{syst.}) \pm 3(\text{lumi.})$ and $\sigma_{\bar{t}} = 91 \pm 4(\text{stat.}) \pm 18(\text{syst.}) \pm 2(\text{lumi.})$ with main systematic uncertainties identified as top-quark modelling and $b$-tagging efficiency. The $R_t$ value is $1.72 \pm 0.09(\text{stat.}) \pm 0.18(\text{syst.})$, in agreement with different PDF sets. The $|V_{tb}|$ is also extracted from the total cross-section being $1.07 \pm 0.09$. ATLAS also measured the fiducial and differential cross-section using $20.2 \, \text{fb}^{-1}$ of data at $\sqrt{s} = 8$ TeV. The fiducial cross-section is measured as $\sigma_{\text{fid}}(t) = 9.78 \pm 0.57$ pb and $\sigma_{\text{fid}}(\bar{t}) = 5.77 \pm 0.45$ pb, in agreement with the MC predictions. The fiducial cross-section is less sensitive to PDF and top-quark modelling effects, and the dominant systematic uncertainty is the JES. The fiducial cross-section is extrapolated to the full phase space and the $|f_{LV}V_{tb}|$ and the $R_t$ are also calculated, being $1.029 \pm 0.048$ and $1.72 \pm 0.09$ respectively. The observed $R_t$ value is compared with different PDF’s predictions and most of them agree at the 1σ level. Differential cross-sections are measured as a function of the $p_T$ and $|y|$ for the top quark and antiquark as well as for the forward jet. To enrich the sample with signal events a cut on the NN is applied. The distributions are unfolded to particle and parton level. The dominant systematic uncertainties are the top-quark modelling and the JES. The results agree with the SM predictions.
3 Top-quark polarisation in single top-quark events

ATLAS and CMS study the top-quark polarisation in $t$-channel single top-quark events. The SM predicts a highly polarised top-quark in the direction of the spectator quark. The top-quark polarisation can be determined from angular distributions of the top-quark decay products reconstructed in the top-quark rest frame given by $1/2(1 + \alpha_l P \cos \theta)$, where $\theta$ is the angle between the top-quark spin axis and the direction of the lepton in the top-quark rest frame, $\alpha_l$ is the spin analysing power, close to one for leptons, and $P$ is the polarisation.

CMS uses a dedicated BDT to suppress $t\bar{t}$, $W$+jets and QCD backgrounds. The differential cross-section as a function of the $\cos \theta$ is unfolded to parton level and the asymmetry, $A = \alpha_l P$, is calculated to be: $A = 0.26 \pm 0.03$(stat.) $\pm 0.10$(syst.). The main systematic uncertainties come from $t\bar{t}$ and $W$+jets modelling. The results are compatible within $2 \sigma$ with the predicted SM asymmetry value of $A = 0.44$.

The ATLAS analysis uses one signal region and two control regions to control the $t\bar{t}$ and $W$+jets background. A series of cuts are applied in order to reduce the background contribution. The $\cos \theta$ distribution is built and unfolded to parton level and the result can be translated into an asymmetry value of $A = 0.49 \pm 0.03$(stat.) $\pm 0.05$(syst.) that corresponds to a top-quark polarisation of $\alpha_l P = 0.97 \pm 0.05$(stat.) $\pm 0.11$(syst.). Dominant systematic uncertainties are top-quark modelling, MC statistics and JES. The results agree with the SM expectations.

4 Single top-quark production in association with a $Z$ boson

The rare SM process of the single top-quark production in association with a $Z$ boson ($tZq$) is studied by CMS using 19.7 fb$^{-1}$ at $\sqrt{s} = 8$ TeV. The signature of these events in the trilepton channel where both the top quark and the $Z$ boson decay leptonically, contains three isolated leptons, $E_T^{\text{miss}}$, one central jet and one forward jet. A BDT is used to separate the signal from the main background that corresponds to diboson events. A fit to the BDT discriminant is performed and the cross-section extracted as $\sigma = 10 \pm 8$ pb with an observed (expected) significance of $2.4 \ (1.8) \ \sigma$. The results are in agreement with the NLO SM cross-section prediction of the three-lepton final state, $\sigma(8$ TeV) = 8.2 fb with a theoretical uncertainty of less than 10%.

5 Conclusion

ATLAS and CMS published interesting and precise single top-quark results in Run 1 and early Run 2. The single top-quark production cross-sections are measured and top-quark properties in single top-quark events are studied. All presented results are consistent with the SM.

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