PROCEEDINGS OF SCIENCE

Measurements of the single top quark production with CMS

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Several measurements of single top quark production in proton-proton collisions at the LHC at centre-of-mass energies of 7, 8 and 13 TeV, using data collected with the CMS experiment, are presented. The analyses investigate separately the production of top quark via t-channel exchange, in association with a W boson (tW) or via the s-channel. Final states with at least one charged lepton and one b-jet are explored to measure inclusive production cross sections. Differential cross section measurements in the t-channel are also reported. The measurements can be used to constrain directly the $|V_{tb}|$ CKM matrix element by comparing with the most precise standard model theory predictions. Measurement of a rare process involving a top quark and a Z boson is also discussed.

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1. Introduction

While most of the top quarks are produced at the LHC in pairs ($t\bar{t}$) through the Quantum-Chromo-Dynamic (QCD) interactions, top quarks can also be produced singly via the electroweak interaction. These production modes provide a unique way to probe the Standard Model (SM) and to measure quantities like the CKM matrix element $|Vtb|$. The three mains single top quark production modes are the $t-$ and $s-$channels and the associated production with a W boson. With the high energy in the center-of-mass and the large luminosity, one can also explore even rarer processes, such as the associated production of a single top quark and a Z boson.

The single top quark signatures offer the possibility to perform several measurements. In the $t-$channel, which is the dominant production mode, the large statistic of events allows to measure the cross section differentially and to probe properties of the top quark production, such as the top quark polarization, the CKM matrix element $|Vtb|$ and to constrain the parton density functions (PDF). The measurements of the tW inclusive cross section is particularly interesting to understand interferences with the $t\bar{t}$ production mode. Finally, the search for rare SM processes, such as the $s-$channel or the associated production of a single top quark in the $t-$channel and a Z boson, are particularly relevant for testing the SM, but are also true experimental challenges. Because they are backgrounds to new physics (BSM) searches, or because they are sensitive to BSM contributions in the Effective Field Theory framework, all single top quark measurements can be used to search for new physics. In this document, I summarize recent measurements of single top quark production cross sections using data collected by the CMS experiment [1] at different center-of-mass energies. Moreover, the first search for the associated production of a single top quark and a Z boson is also discussed.

2. Measurements of inclusive and differential $t-$channel cross sections

The t-channel signature is composed of a single top quark produced in association with a recoiling light quark, that is mainly located in the forward region of the detector. The leptonic decay channel of the top quark is analyzed, and the event selection starts then with a single lepton trigger requirement. Two high jets with high transverse momentum (p_T) are then selected, with one of them being potentially forward (up to $\eta = 4.5$) while the second one has to be more central ($\eta < 2.5$) and potentially identified as a b-jet. The signal extraction is done by mean of a likelihood fit (with systematics uncertainties accounted as nuisance parameters) performed simultaneously on three different samples, defined by different jet and b-tagged jet multiplicities :

- the "2 jets, 1 tag" (2J1T) sample contains most of the signal events but suffers from large $t\bar{t}$ and W+jets backgrounds contamination,
- the $t\bar{t}$ background is constrained from the 3J0T and 3J1T samples,
- the W+jets background is validated and constrained using 2J0T events.

The discriminating variables used in the likelihood fit is a Neural Network output, constructed from kinematic and mass variables such as the pseudo-rapidity of the recoiling jet ($|\eta(j')|$, the reconstructed top quark mass m_t, the di-jet invariant mass or the transverse mass of the reconstructed W boson $m_T(W)$.

The measured cross section [2] at 13 TeV, extracted from a dataset of 2.2 fb^{-1} of proton-proton collisions, is 238 $\pm$ 13 (stat) $\pm$ 29 (syst) pb. The ratio of the top quark cross section to the antitop quark cross section is found to be $R[t-ch.]$ = 1.81 $\pm$ 0.18 (stat) $\pm$ 0.15 (syst) . From the total cross section, the absolute value of the CKM matrix element V_{tb} can also be calculated according to the formula $f_{LV}|V_{tb}| = \sqrt{\sigma_{t-ch,t+\bar{t}}/\sigma^{theo.}_{t-ch,t+\bar{t}}}$, with $\sigma_{t-ch,t+\bar{t}}$ the measured cross section and $\sigma^{theo.}_{t-ch,t+\bar{t}}$ the cross section predicted by the SM. $f_{LV}|V_{tb}|$ is found to be 1.05 $\pm$ 0.07 (exp) $\pm$ 0.02 (theo).

With the larger cross section and the high luminosity, the $t-$channel cross section can be measured differentially. The corresponding analyses [3, 4] are using very similar event selection and signal extraction as for the inclusive cross section. They however minimise biases from event selection and include an unfolding to parton level. The differential cross section as a function of the top quark p$_T$ is shown on the left plot of Fig. 1, for 2.2 fb^{-1} of 13 TeV data [3], while the right plot of Fig. 1 shows the differential cross section as a function of $cos\theta^*$ using Run I data at 8 TeV [4]. The variable $cos\theta^*$ is defined as cosine of the angle between the charged lepton in top-quark rest frame and recoiling jet.

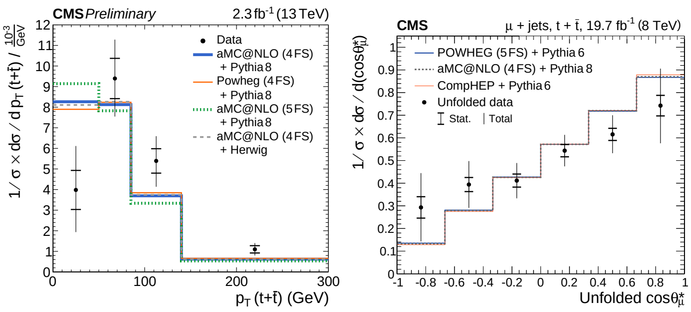

Figure 1: Measured differential cross section of $t-$channel single top quark production, unfolded to the parton level, as a function of the top quark transverse momentum at 13 TeV [3] (left) and as a function of $cos\theta^*_\mu$ at 8 TeV [4] (right). Horizontal ticks on the error bars indicate the statistical uncertainty and vertical bars indicate the total uncertainty per bin. Measurements are compared to different Monte Carlo predictions, obtained from different generators, parton shower programs and flavor schemes.

3. Measurements of tW cross section and search for the s-channels

The two other dominant single top quark production modes are more difficult to observe. The tW-channel has been observed in the dilepton channel, where there is a better signal-to-background balance compared to the single lepton channel. The analysis is performed by requiring two opposite-charge high-p_T leptons, either electrons or muons, at least 1 jet and at least 1 b-tagged jet. In the ee and $\mu\mu$ channels, additional selections on the dilepton invariant mass and the missing transverse energy are applied, in order to reject the Z/γ^* background. Then, different samples are defined by applying different selection on the jet and b-tagged jet multiplicities. The 1J1T region is the one with the highest fraction of signal events. The 2J1T and 2J2T regions are mainly used to constrain the backgrounds using a simultaneous likelihood fit, where systematics are accounted as nuisance parameters. The fitted distributions are based on Boosted Decision Trees (BDTs) which disentangle signal events from the backgrounds. The most discriminating variables used in the training are the jets and b-tag jets multiplicities of low p_T jets. The dominant systematics uncertainties are related to the modeling of signal and $t\bar{t}$ events. This analysis leads to the first observation of the tW process [5], with a significance of 6.1 standard deviations and a cross section measured to be 23.4±5.4 pb at 8 TeV. The left plot of Fig 2 shows the BDT discriminant in the 1J1T region [5].

In the s-channel, it is even more difficult to extract the signal because of the overwhelming $t\bar{t}$ background. The analysis is performed in the single lepton channel, with combining the 7 and 8 TeV datasets, the strategy is similar as for the single top $t-$channel analysis. Events with one high p_T lepton and 2 jets are selected and then categorized depending on their jet and b-tagged jet multiplicities. The 2J2T region contains most of the signal, while 2J1T and 3J2T regions are used to constrain the data using a likelihood fit of BDT output distributions. The analysis is dominated by the statistical uncertainty and the highest systematic contributions come from the uncertainties on the modeling of signal and $t\bar{t}$ events. The expected and observed significances are 1.1 and 2.5 respectively [6]. The right plot of Fig 2 shows the BDT discriminant in the 2J2T event category, in the electron channel at 8 TeV [6].

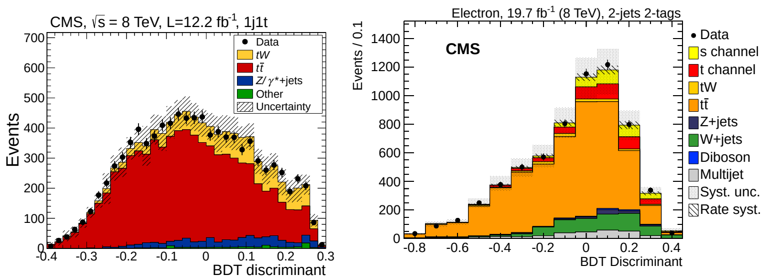

Figure 2: Left [5] : the BDT discriminant in the tW-channel, in the signal region 1J1T and for all final states combined. Shown are data (points) and simulation (histogram). The hatched band represents the combined effect of all sources of systematic uncertainty. Right [6] : Comparison of data with simulation for the distributions of the BDT discriminants in the 2J2T event category for the $s-$channel analysis, for the electron channel at 8 TeV. The simulation is normalized to the combined (7+8 TeV) fit results. The inner uncertainty bands include the post-fit background rate uncertainties only, the outer ones include the total systematic uncertainty, obtained summing in quadrature the individual contributions.

4. Search for the single top quark production in association with a Z boson

The large luminosity at the LHC allows searching for even rarer processes, such as the associated production of a single top quark in the t-channel and a Z boson, labelled tZq in the following. The analysis [7] is performed in the three leptons, with leptons being either electrons or muons. At 8 TeV, the cross section in the tri-lepton channel is of 8.2 fb, as predicted by the SM. The selection asks for three leptons, with a pair of same flavor opposite sign leptons giving an invariant mass compatible with a Z boson. In addition, the selection requires at least 2 jets, potentially in the forward region or b-tagged. A minimum requirement on the transverse mass of the W boson is also applied to reject Z/γ^* events. The signal is extracted from a BDT discriminant in the 2J1T region, while the non-prompt lepton background is constrained from data using events in the 1-2J0T region. The BDT discriminant in the signal region and the transverse mass of the W boson in the control region are shown in Fig. 3 [7]. The measured cross section is of 10^{+8}_{-7} fb, with the corresponding observed (expected) significance being 2.4 (1.8) standard deviations respectively.

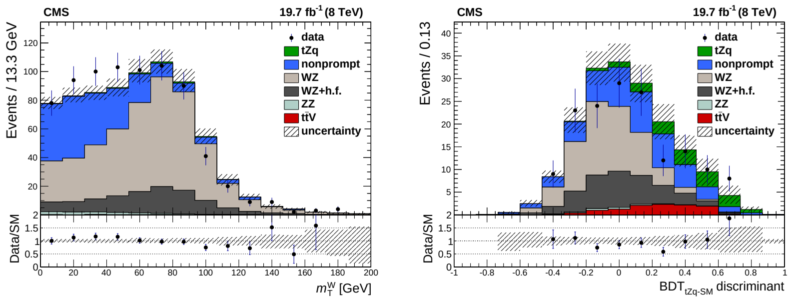

Figure 3: For the tZq process, data-to-prediction comparisons after performing the fit for $m_T(W)$ distribution in the control region (left) and for the BDTtZq-SM responses in the signal region (right). Figure taken from [7]

5. Summary

This proceeding presents the CMS measurements of the single top quark cross sections at the LHC. These measurements enter into a new area, as the very high luminosity, and the high energy in the center of mass, open up many opportunities for probing the SM and the electro-weak interaction. First, the inclusive cross sections of the t-channel reached unprecedented precisions, and differential measurement is now possible. In addition, with the increasing statistics and with new data at 13 TeV, a significant increase of precision is expected for tW- and s-channels, and even rarer processes will start to be observable.

References

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