PROCEEDINGS OF SCIENCE

Single top and V_{tb} measurements

Soureek Mitra*
(on behalf of the ATLAS and CMS collaborations)
Tata Institute of Fundamental Research, Mumbai, India
E-mail: soureek.mitra@cern.ch

Measurements of single top quark production are presented, based on the LHC data collected at centre-of-mass energies of 7, 8 and 13 TeV. The cross sections for the electroweak production of single top quarks in the t-channel as well as in association with W bosons are measured and the results are used to estimate the CKM matrix element V_{tb}. In the t-channel, the ratio of top and anti-top production cross sections is determined and compared with predictions from different parton density distribution functions. Searches dedicated to the s-channel production at the LHC are also discussed. Further, searches for presence of any anomalous interactions at the tWb vertex beyond the predictions of the standard model are presented. These searches are carried out in the t-channel production mode by performing measurements of top polarization, helicities etc. from its decay products. Limits are obtained to constrain new physics.

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*Speaker.

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1. Introduction

The top quark, heaviest among all known elementary particles, is unique in a number of ways. It decays ($\tau_{\text{dec}} \approx 10^{-25}$s) via electroweak interaction before hadronization ($\tau_{\text{had}} \approx 10^{-24}$s), implying that it can exist as a free quark before decaying. Thus it proves to be an excellent probe for signatures of physics beyond the standard model (SM) through comparison of measurements with precise SM predictions. Top quarks are produced copiously in the proton-proton (pp) collision at the Large Hadron Collider (LHC) dominantly via pair production ($t\bar{t}$) followed by single top processes. Single top quarks are produced through charged-current interaction via exchange of a W boson, unlike the dominant $t\bar{t}$ production process, which occurs through strong interaction. The electroweak nature of the interaction in single top production implies the cross section (σ) to scale as the square of the absolute value of Cabibbo-Kobayashi-Masakawa (CKM) matrix element V_{tb}, i.e., $\sigma \propto |V_{tb}|^2$. Thus, $|V_{tb}|$ can be directly estimated through single top processes by comparing their measured cross sections with theoretical predictions, which assumes $|V_{tb}| \approx 1$.

Single top production at the LHC can be characterized via 3 modes: t-channel, tW-channel and s-channel, as shown in Figure 1, in decreasing order of cross section. In addition to $|V_{tb}|$, other fundamental SM parameters, such as top quark mass, polarization etc. can also be measured using these processes. It provides a direct probe to the tWb coupling structure for any beyond-the-SM (BSM) contribution such as the presence of anomalous tensor couplings [1], fourth generation, flavor changing neutral current, new resonances like W′ [2], charged Higgs ($H^{\pm}$)[3] etc. Differential measurements can also provide powerful inputs to constrain the b-quark parton distribution function (PDF) at high momentum fractions [4].

In this paper, recent measurements of single top cross sections in different modes along with corresponding estimates of V_{tb}, studies directed at probing the coupling structure of the tWb vertex through measurements of top quark polarization and searches for anomalous couplings, are presented. The events are categorized depending on the number of jets and the number of b-tagged jets to define the signal and control regions for analyses. A generic nomenclature "NjMt" is attributed to the events with N jets and M b-tagged jets. Measurements are performed in final states where the top quark decays to a b-quark and a W boson and the W boson, in turn, decays leptonically to electron or muon (e or μ) directly and through cascade (via τ lepton decays) giving rise to large missing transverse energy ($\not{E}_T$) due to the escaping neutrino(s).

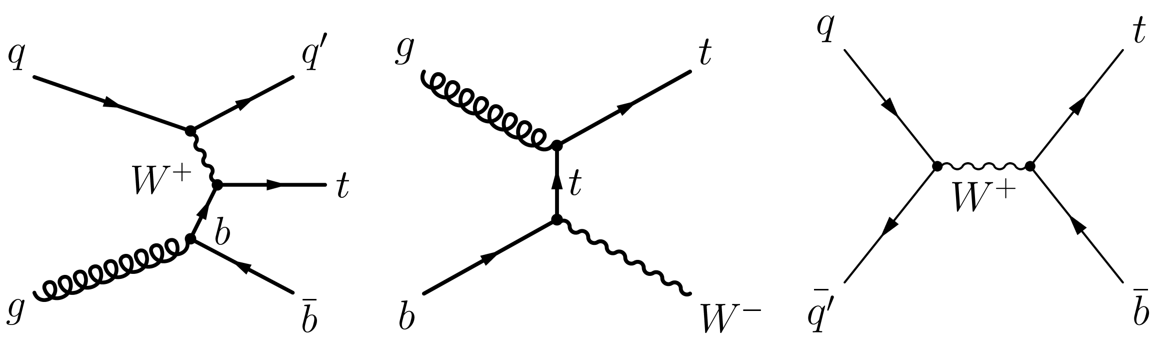

Figure 1: Feynman diagrams of single top production in the standard model: t-channel (left) , tW-channel (middle) and s-channel (right).

2. Cross section and V_{tb} measurements

- **t-channel:** The t-channel is the most abundant single top production mode and is therefore the most studied. Both ATLAS [5] and CMS [6] have measured t-channel cross section with the recent data collected at $\sqrt{s}$ =13 TeV [7, 8]. A striking feature of this process is the presence of a jet in the high pseudorapidity region due to the light flavor quark recoiling against the top. So the final state consists of an isolated lepton with high transverse momentum (p_T), two jets due to hadronization of the light quark and b-quark (2j1t) and large $\not{E}_T$. The most dominant backgrounds to this final state are $t\bar{t}$ and W boson produced in association with jets (W+jets). Orthogonal control regions with different jet and b-tagged jet multiplicities are used to estimate these backgrounds or validate Monte Carlo (MC) models used for their predictions. QCD multijet events also constitute a non-negligible background for which a reliable estimation is performed with a control region obtained by inverting the lepton isolation requirement while fulfilling all other selection criteria. Multivariate (MVA) analyses have been performed by both collaborations for better discrimination of signal from backgrounds, utilizing the full potential of the data collected at 13 TeV. The signal cross section is extracted by means of a likelihood fit to the MVA discriminator distribution. The ratio ($R_{t-ch} = \frac{\sigma_t}{\sigma_{\bar{t}}}$) of production rates of top and anti-top quarks in the t-channel has also been measured by both CMS and ATLAS. The values agree with each other and with the predictions from different PDF sets within uncertainties. In general, $|V_{tb}|$ is estimated in all single top channels using
$$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{\text{measured}}}{\sigma_{\text{theory}}}}, \tag{2.1}$$
where f_{LV} is the anomalous form factor [1] covering for any BSM contribution at the tWb vertex and f_{LV} equals to 1 for SM. The estimated values of $|V_{tb}|$ in the t-channel from CMS and ATLAS agree with each other as well as with the SM predictions within uncertainties. The uncertainties in the measured/estimated values are dominantly due to systematics related to modeling of signal and background processes in simulation, modeling of parton showering, PDF, jet energy scale (JES) etc. CMS provides the most accurate measurement of the total cross section in the t-channel single top production at $\sqrt{s}$ = 13 TeV.
  CMS has also performed a differential cross section measurement [9] with top quark p_T and absolute rapidity (|y|) in the final state having one high p_T isolated μ. In this analysis, unfolding is performed to the background subtracted data in a signal-enriched region obtained by applying criterion on MVA discriminant. The top p_T spectrum in data is found to be harder compared to different simulations.

- **tW-channel:** The tW-channel is the second most abundant single top production mode at LHC. It is difficult to perform measurements in this channel as it has significant interference from $t\bar{t}$ at next-to-leading-order (NLO) to the matrix element (ME), the effect of which is not estimated accurately in simulations. Thus $t\bar{t}$ constitutes an irreducible background to the tW-channel signal. Still it had been discovered experimentally at the LHC in the di-lepton (ee, $e\mu$ and $\mu\mu$) final states, independently by CMS and ATLAS collaborations with Run-I data collected at $\sqrt{s}$ = 8 TeV [10, 11]. These measurements have been combined [12, 13] taking into account the correlation in the (systematic) uncertainties to achieve an overall precision of 16%, which is lower compared to the precision of the individual measurements (CMS: 23%, ATLAS: 17%) . Uncertainties due to initial and final state radiation, renormalization/factorization (μ_R/μ_F) scale, parton shower (PS) modeling, ME-PS matching threshold etc. are the dominant ones. The V_{tb} value is also estimated from the measured cross section using Eq.(2.1).

A brand new measurement of the tW-channel production cross section is performed by the ATLAS collaboration [14] with the data collected at $\sqrt{s}$ = 13 TeV in the di-lepton final states.1j1t and 2j2t are considered to be signal regions, and two different boosted decision trees (BDTs) are trained to separate tW-channel single top signal from $\mathrm{t\bar{t}}$ background. The normalization of $\mathrm{t\bar{t}}$ is controlled using 2j2t events. The measurement is in agreement with the SM prediction and corresponds to a signal significance of 4.5 standard deviations, strongly indicating towards the re-discovery of the tW-channel at 13 TeV. JES, modeling of NLO ME, PS and hadronization modeling etc. are the dominant uncertainty sources.

- **s-channel:** This is the least abundant single top production mode at the LHC. The discovery of this process with significance exceeding 5 standard deviations has not yet been achieved. Low cross section coupled with large contamination from $\mathrm{t\bar{t}}$ background makes it very challenging to perform measurements in s-channel, though it is most sensitive to new resonances like $\mathrm{W'}$ and heavy $\mathrm{H^{\pm}}$ etc. In the final state, there is a high-$\mathrm{p_T}$ isolated lepton and 2 b-tagged jets. Top pair production constitutes the irreducible background with W+bb, t-channel single top etc. playing a sub-dominant role.

ATLAS has performed an analysis [15] with 20.3 $\mathrm{fb^{-1}}$ data collected at $\sqrt{s}$ =8 TeV by using a matrix element method to separate signal from background. In this method, the probability $P(\mathrm{S|X})$ of an event to be signal-like is estimated using Eq.(2.2) from the final state configuration (X) of the selected lepton and jets.

$$P(\mathrm{S|X}) = \mathrm{P_S}(\mathrm{p}^{\mu}_{\ell},\mathrm{p}^{\mu}_{\mathrm{j1}},\mathrm{p}^{\mu}_{\mathrm{j2}}) = \frac{1}{\sigma}\int \mathrm{d}\rho_{\mathrm{j1}}\mathrm{d}\rho_{\mathrm{j2}}\mathrm{dp}^{\nu}_{\mathrm{z}} \sum_{\mathrm{comb}} \Phi^4 |\mathscr{M}(\mathrm{p}^{\mu}_{\mathrm{i}})|^2 \frac{\mathrm{f(q_1)f(q_2)}}{|\mathrm{q_1}||\mathrm{q_2}|}\mathscr{W}(\mathrm{E_{jet}},\mathrm{E_p}), \tag{2.2}$$

where $\mathrm{p}^{\mu}_{\ell},\mathrm{p}^{\mu}_{\mathrm{j1}}$ and $\mathrm{p}^{\mu}_{\mathrm{j2}}$ are the 4-momentum vectors of the selected lepton and jets, $\mathscr{M}(\mathrm{p}^{\mu}_{\mathrm{i}})$ is the matrix element calculated at leading order (LO), $\mathrm{f(q_1)}$ & $\mathrm{f(q_2)}$ are the PDFs of the impinging partons, $\mathscr{W}(\mathrm{E_{jet}},\mathrm{E_p})$ is the probability of measuring a jet having energy $\mathrm{E_{jet}}$ originating from a parton having energy $\mathrm{E_p}$. The integral is performed over part of the phase space which is denoted by Φ^4. A profile likelihood fit of signal and background templates of $P(\mathrm{S|X})$ is performed to data. Comparing background only and signal+background hypotheses, evidence of s-channel single top is found with a significance of 3.2 standard deviations. The measured s-channel cross section is σ_{s-ch} = 4.8$\pm$0.8(stat.)$^{+1.6}_{-1.3}$(syst.) pb, which agrees with the SM prediction σ^{SM}_{s-ch} = 5.2$\pm$0.2 pb, within uncertainties. The precision of this measurement is limited by data statistics.

CMS has searched [16] for the s-channel single top signal in the final state having one high $\mathrm{p_T}$ isolated lepton and two b-tagged jets (2j2t) with the combined data collected during Run-I at 7 and 8 TeV. BDTs are trained to separate expected signal contribution from backgrounds in the 2j2t region. Maximum-likelihood fit to the data distribution of the BDT discriminant is performed to extract signal. A signal significance of 2.5 standard deviations is achieved, and an upper limit, on the rate relative to the SM expectation, of 4.7 at 95% confidence level is obtained.

The summary of LHC measurements of single top cross section at different centre-of-mass energies for all single top channels are shown in Figure 2 and the corresponding V_{tb} measurements are shown in Figure 3.

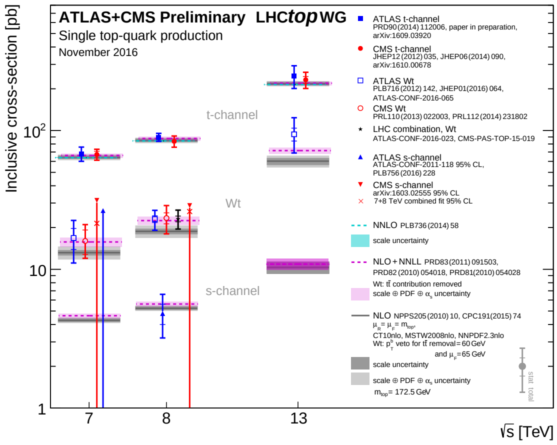

Figure 2: Summary of single top cross section measurements at LHC [17].

3. Probing the tWb vertex using single top events

The top quark provides a unique opportunity to study "bare" quark properties due to a neat separation of the relevant time scales: the production time ($\approx \frac{1}{m_{top}}$, where $m_{top} \approx$175 GeV) is two orders of magnitude smaller than its lifetime ($\frac{1}{\Gamma_{top}}$, where $\Gamma_{top} \approx$ 2 GeV), which is an order of magnitude smaller than the hadronization time-scale ($\approx \frac{1}{\Lambda_{QCD}}$ with $\Lambda_{QCD} \approx$ 0.2 GeV), which in turn, is also an order of magnitude smaller than the spin de-correlation time ($\approx \frac{m_{top}}{\Lambda^2_{QCD}}$). This implies that top decay products remember its helicity information since its lifetime is shorter than the spin de-correlation time. This is a very powerful tool to probe for anomaly in the tWb coupling due to BSM effects. The t-channel having the largest cross section among the three production modes provides a useful playground to probe for new physics through the tWb coupling.

The (V-A) coupling structure of tWb vertex in SM predicts that the top quark is fully polarised in the momentum direction of the light quark recoiling against the top [18, 19]. New physics can show up if de-polarisation is observed in the electroweak production or decay of the top quark which indicate an alteration of the tWb coupling. In the top rest frame, angular distribution (θ^*_X) of a decay product X with respect to spin direction of the top quark can be written as

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_X} = \frac{1}{2}(1 + P^{(S)}_t \alpha_X \cos\theta^*_X) = \frac{1}{2} + A_X \cos\theta^*_X \tag{3.1}$$

where $A_X = \frac{1}{2}P^{(S)}_t \alpha_X$, with $P^{(S)}_t$ being the top polarisation (due to production vertex) along its spin direction, α_X being the spin-analysing power of the decay particle X ($\approx$ 100% for charged lepton)

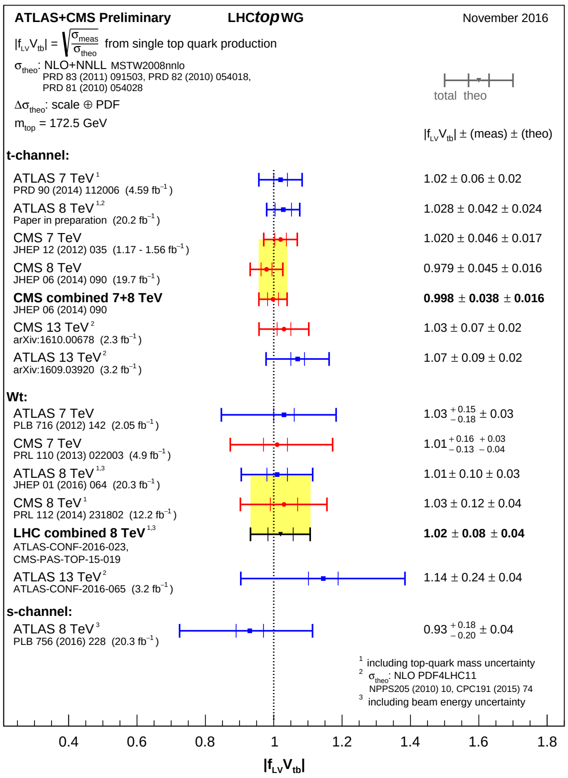

Figure 3: Summary of V_{tb} measurements at LHC [17].

and θ^*_X being the angle between the decay product X and the recoiling jet in the top quark rest frame. Both $P_t^{(S)}$ and α_X can be affected due to change in coupling structure in the tWb vertex. The SM expectation is $P_t^{(S)}\alpha_X \approx 1$ for the muonic decay product ($X = \mu$). A dedicated measurement of the top polarisation has been performed by CMS with 8 TeV data in a t-channel single top enriched sample [20]. The observed distribution of $\cos\theta^*_\mu$ is used to infer the differential cross section as a function of $\cos\theta^*_\mu$ that is found to have linear behavior as expected in the SM, but with a slope A_μ = 0.26±0.11, which is 2 standard deviations away from the SM prediction A_μ^{SM} = 0.44.
The SM lagrangian for the tWb vertex can be minimally extended to have a more general form as given in Eq.(3.2) which predicts anomalous vector and tensor couplings in addition to the (V-A) coupling structure from the SM. These additional tensor couplings can alter the polarization of the top quark and helicity fractions of the W boson from its decay.

$$\mathscr{L}^{\text{anom.}}_{tWb} = -\frac{g_w}{\sqrt{2}}\bar{b}\gamma^\mu(f_L^V P_L + f_R^V P_R)tW^-_\mu - \frac{g_w}{\sqrt{2}}\bar{b}\frac{-i\sigma^{\mu\nu}q_\nu}{M_W}(g_L P_L + g_R P_R)tW^-_\mu + \text{h.c}, \quad (3.2)$$

where g_w is the weak coupling constant, M_W is the mass of W boson and q_ν is the 4-momentum of the W boson. $P_{L,R} = \frac{(1\mp\gamma^5)}{2}$ are the left- and right-handed projection operators, $\sigma^{\mu\nu} = \frac{i[\gamma^\mu,\gamma^\nu]}{2}$, $f^V_{L,R}$ and $g_{L,R}$ are the complex left- and right-handed vector and tensor couplings, respectively. In the SM, $f_L^V = V_{tb}$ and $f_R^V = g_{L,R} = 0$ at tree level.
ATLAS has performed a measurement of angular distributions of the lepton from the top decay in t-channel single top events using 4.6 fb^{-1} data collected at $\sqrt{s} = 7$ TeV [21]. After selecting a

relatively pure sample, a likelihood is constructed from the 2-D probability density of (cos$\theta*$,$\phi*$) and fitted to data, where $\theta*$ is the angle between lepton momentum in the W rest frame and W momentum in the top rest frame and $\phi*$ is the complementary azimuthal angle. Limits are extracted on the ratios of complex coupling parameters g_R to f_L^V, at 95% confidence level, to be Re[g_R/f_L^V] $\in [-0.36,0.10]$ and Im[g_R/f_L^V] $\in [-0.17,0.23]$, which are consistent with the SM. ATLAS has extracted a list of polarization observables for top and W from several asymmetry measurements in different angular distributions with 20.3 fb^{-1} data collected at $\sqrt{s} = 8$ TeV [22]. A relatively pure sample of t-channel single top events is selected to measure angular distributions which are then unfolded at the parton level after background subtraction. Angular asymmetries are then derived from the unfolded distributions and a limit Im[g_R] $\in [-0.17,0.06]$ has been extracted.
CMS has performed a combined analysis on the full Run-I data collected at 7 and 8 TeV to search for anomalous vector and tensor couplings in t-channel single top events having a high p_T isolated muon in the final state [23]. In this analysis, dedicated neural networks (NNs) are trained for four different anomalous couplings of the tWb vertex along with an NN for the SM coupling. Two or three anomalous couplings are simultaneously floated in 2-D or 3-D fits to data. Limits have been extracted to be $f_L^V > 0.98$, $|f_R^V| < 0.16$, $|g_L| < 0.057$ and $-0.049 < |g_R| < 0.048$, by performing a simultaneous fit to the NN distributions corresponding to the SM coupling and anomalous tWb couplings.

4. Conclusions

Precise measurements of the t-channel single top cross section at $\sqrt{s} = 13$ TeV have been performed at the LHC, with results in agreement with the SM within uncertainties. R_{t-ch} has been extracted from the measurements that provides an extra handle to constrain u/d PDF and also allows a measurement of b-quark PDF. Current measurements are mostly dominated by uncertainties due to modeling systematics. This is a limiting factor for a more precise estimation of V_{tb}. Better understanding and validation of MC generators is required to overcome such issue. A more precise tW-channel cross section measurement is expected soon. Experimental observation of the s-channel single top process continues to remain a steep struggle at the LHC. It should be given more importance at $\sqrt{s} = 13$ TeV as it is very sensitive to new resonances from BSM scenarios. An LHC-wide combination of single top cross section and V_{tb} measurements with the Run-I data is ongoing. More precision is required in order to improve limits on anomalous couplings at the tWb vertex. The whole community is eagerly waiting for exciting surprises, yet to be revealed, during the era of the LHC.

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