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$t\bar{t}$ cross section measurements at the Tevatron

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Summary. — We review recent measurements of the $t\bar{t}$ cross section measurements in proton anti-proton scattering performed by the CDF and DØCollaborations at a center-of-mass energy of $\sqrt{s} = 1.96\,\text{TeV}$ at the Tevatron. The measurements in several top decay channels are described with the corresponding background estimations. Several top quark properties extracted from these measurements are also discussed, namely the top quark mass extraction from cross section measurement, ratios of $t\bar{t}$ cross sections, the measurement of the $t\bar{t}$+jets cross section and some differential cross section measurements.

PACS 14.65.Ha – Top quarks.

1. – Introduction

The top quark is a very special quark since it is the highest elementary particle in the Standard Model (SM). Due to its large mass, its Yukawa coupling is close to unit which may indicate that the top quark may have a special function in the electroweak symmetry breaking mechanism. So top quark physics plays an important role in testing the SM. As part of this program we are interested to measure the top quark strong production mechanism: *i.e.* the $t\bar{t}$ cross section. It allows to compare the measurement with the QCD predictions and to check the $t\bar{t}$ selection to be used in other top properties measurements. In addition, comparing the measurements in all different channels can give constraints on physics beyond the SM.

We will first describe briefly the $t\bar{t}$ production mechanism at the Tevatron as well as the method used to measure the cross section. Then we will review the measurements in the lepton+jets, dilepton and all-hadronic channels as well as some extra information that can be extracted from these measurements. Finally we will describe the $t\bar{t}$+jets and differential cross section measurements.

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2. – $t\bar{t}$ production mechanism and cross section measurement method

At the Tevatron the top quark is mainly produced via the strong interaction in top-antitop pair. In the SM, the produced (anti-)top quark decays nearly 100% of the time into a W boson and a b quark. The $t\bar{t}$ final states are then classified according to the decay channels of the two W bosons. Computations of the $p\bar{p} \to t\bar{t}$ total rate are available at NLO [1]. Several approximate NNLO computations where the dominant (next to) next-to-leading logarithm are resummed allowing a lower sensitivity to the renormalization and factorization scales are also available [2-5]. For a 172.5 GeV top quark mass, the more recent calculations for the $t\bar{t}$ cross section at Tevatron predict a cross section around 7.5 pb with a relative precision around 8%.

At LHC, the $t\bar{t}$ cross section for a 172.5 GeV top quark mass is roughly 20 times higher for pp collisions at a center-of-mass energy of 7 TeV. Assuming that the selection efficiency in the lepton+jets channel will be comparable ($\sim$ 10% requesting 4 jets), then the number of selected $t\bar{t}$ events in this channel in one LHC experiment with 1 fb^{-1} of data will be approximatively twice the number of selected $t\bar{t}$ events in one experiment at the Tevatron with 10 fb^{-1} of data. The Tevatron experiments have already collected a large sample of $t\bar{t}$ events, hence a lot of the $t\bar{t}$ cross section measurements presented here are already systematically limited.

The $t\bar{t}$ cross section measurement is performed by evaluating the following formula:

$$\sigma_{t\bar{t}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\epsilon_{t\bar{t}} \int \mathcal{L} \mathrm{d}t}, \tag{1}$$

where N_{obs} is the observed number of events after selection in the data sample and N_{bkg} is the estimated number of background events. $\epsilon_{t\bar{t}}$ is the signal efficiency evaluated using $t\bar{t}$ Monte Carlo and $\int \mathcal{L}\mathrm{d}t$ is the analyzed integrated luminosity for the particular set of triggers used for the measurement. It has to be noticed that $\epsilon_{t\bar{t}}$ is increasing with the top quark mass, hence the measured cross section is quoted at a given top quark mass. The numerator in (1) can be evaluated either using event counting after applying the selection cuts or by fitting a discriminant variable that separates signal and background. The use of b-jet identification can be an important tool to discriminate signal from background.

B-tagging utilizes the special properties of b-jets coming from the hadronization of b quarks to separate them from light or gluon initiated jets. Three main b-tagging algorithms can be used based on either the measurement of the impact parameter, the reconstruction of secondary vertices or soft lepton tagging. The information from these algorithms can also be combined using multivariate method. Typically the b-tagging efficiency is 55% for a mis-tagging rate of 1%.

3. – $t\bar{t}$ cross section in the lepton+jets channel

In this channel one of the W bosons from the decay of the (anti)-top quark is decaying into one electron, one muon (or one τ lepton that further decays into an electron or a muon), while the other is decaying into two quarks. We end up with at least four jets in the events among which two are jets from b quarks. This final state has the advantage of a reasonable branching ratio while keeping the background to a manageable level.

The main physics processes which can mimic a $t\bar{t}$ event in this channel are, by order of importance, W+jets production, QCD multijet processes, Z+jets, diboson production (WW, ZZ, WZ) and electroweak produced single top production. Z+jets, diboson and single top backgrounds are evaluated using MC normalized to (N)NLO theoretical cross sections. The QCD multijet background is estimated using data. DØ is using the so-called matrix method [6] to estimate it. It consists of solving a 2D system of linear equations based on the number of events in two datasets defined as

$$
\begin{aligned}
N_{\text{loose}} &= N_{\text{QCD}} + N_{\text{sig}}, \\
N_{\text{tight}} &= \epsilon_{\text{QCD}} N_{\text{QCD}} + \epsilon_{\text{sig}} N_{\text{sig}},
\end{aligned} \tag{2}
$$

where N_{loose} is the number of events in a data sample with loose lepton isolation, while N_{tight} is the number of events in the subsample with tight lepton requirement. N_{QCD} is the number of QCD multijet events in the sample we want to determine and N_{sig} is the number of events that does not come from multijet events (dominated by W+jets and $t\bar{t}$ events). ϵ_{sig} is the efficiency for a loose lepton from a W boson decay to pass the tight criteria. ϵ_{QCD} is the rate at which a loose lepton from QCD multijet events is selected to be tight. ϵ_{QCD} is measured in a data sample with low transverse missing energy ($\not{E}_T$).

CDF is using a slightly different method. To obtain the number of QCD multijet background events a fit of the $\not{E}_T$ distribution to a combination of QCD multijet and W+jets shapes is performed. The shape for QCD multijets is formed from data events that fail at least two lepton identification criteria. The fraction of QCD multijet events in the high $\not{E}_T$ region is then extracted from the fit of the low part of the $\not{E}_T$ distribution.

For the W+jets production, no reliable NLO calculation exists that can get the W+jets cross section right. Therefore we derive the normalization from data and use only the shape from MC.

The total amount of W+jets contribution is normalized to the number of events in data minus the estimated number of $t\bar{t}$, QCD multijet and electroweak processes. Among the W+jets events the contribution from W associated with jets from heavy flavor (HF) b and c quarks is found to be underestimated in the MC simulation. Then an additional scaling determined on data is applied to the W+HF MC samples. The W+HF content is measured in data events with one or one and two jets. The corresponding scale factor is then used to correct the W+HF samples in events with higher jet multiplicity.

Measurements in the lepton+jets channel are performed using either purely topological information or b-tagging. The topological measurement uses the output of a multivariate discriminant from either a neural network (NN) for CDF or a boosted decision tree (BDT) for DØ to further discriminate $t\bar{t}$ signal from the dominant background coming from W+jets events. These discriminants exploit the differences in kinematic properties between signal and background. Input variables like $H_T = p_{T\,\text{lepton}} + \sum p_{T\,\text{jets}}$, the aplanarity and sphericity, the invariant mass of the lepton, ... are used as inputs to the multivariate discriminant. Multivariate output templates for the $t\bar{t}$ signal and for the multijet, W+jets and diboson backgrounds are then formed and used in a likelihood fit of the NN or BDT output distribution to extract the value of the measured $t\bar{t}$ cross section.

Using 4.6 fb^{-1} of data, CDF using topological information only measures [7]: $\sigma_{t\bar{t}} = 7.71 \pm 0.37\ (\text{stat}) \pm 0.36\ (\text{syst}) \pm 0.45\ (\text{lumi})\,\text{pb}$ while DØ [8] using 4.3 fb^{-1} measures: $\sigma_{t\bar{t}} = 7.70^{+0.79}_{-0.70}\ (\text{stat} + \text{syst})\,\text{pb}$ for a 172.5 GeV top quark mass. These measurements are systematically limited. Apart from the uncertainty on the luminosity, the dominant sources of systematic uncertainties on these measurements are the uncertainties on the jet energy scale, jet energy resolution and signal modeling. The precision of these measurements is around 9%.

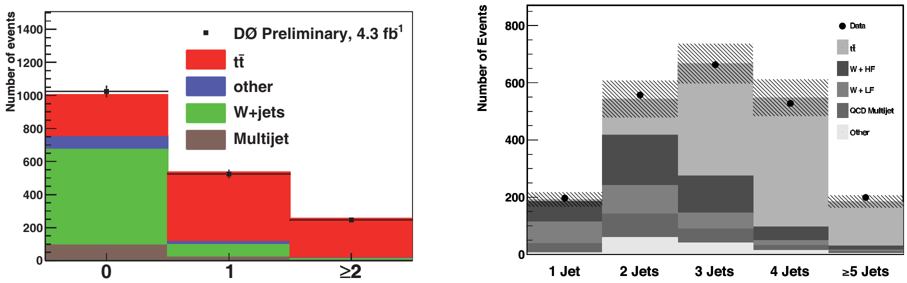

Fig. 1. – Distribution for the number of b-tagged jets in DØ (left) and for the number of jets in CDF (right) in the lepton+jets channel.

Besides the method using pure topological information the data sample can alternatively be enriched in $t\bar{t}$ events by applying b-tagging. In that case the amount of W+light jet events when a jet is wrongly identified as a HF jet is measured on data and this probability is then applied to MC W+light jets samples prior to apply b-tagging. Using $4.3\,\text{fb}^{-1}$ of data, CDF measures [7]: $\sigma_{t\bar{t}} = 7.22 \pm 0.35\,(\text{stat}) \pm 0.56\,(\text{syst}) \pm 0.44\,(\text{lumi})\,\text{pb}$ while DØ [8] using $4.3\,\text{fb}^{-1}$ measures: $\sigma_{t\bar{t}} = 7.93^{+1.04}_{-0.91}\,(\text{stat}+\text{syst})\,\text{pb}$ for a 172.5 GeV top quark mass. Apart from the uncertainty on the luminosity, the dominant source of systematic uncertainties in that case comes from the estimation of the W+HF background and from the b-tagging uncertainty. Figure 1 shows the distribution for the number of jets in both CDF and DØ.

The largest systematic uncertainty on both the topological and b-tagging measurements is the uncertainty on the luminosity which is around 6%. It can be effectively removed by measuring the ratio of this $t\bar{t}$ cross section with the inclusive $Z/\gamma^* \to \ell\ell$ cross section. This experimental ratio can then be multiplied by the theoretical $Z/\gamma^* \to \ell\ell$ cross section:

$$\sigma_{t\bar{t}} = \left(\frac{\sigma_{t\bar{t}}}{\sigma_{Z/\gamma^*\to\ell\ell}}\right)_{\text{meas}} (\sigma_{Z/\gamma^*\to\ell\ell})_{\text{theor}}. \tag{3}$$

Hence the luminosity uncertainty is traded with the theoretical uncertainty on the Z/γ^* cross section which is smaller. The inclusive $Z/\gamma^* \to \ell\ell$ cross section is measured using consistent trigger requirements and lepton identification with the $t\bar{t}$ cross section. With $(\sigma_{Z/\gamma^*\to\ell\ell})_{\text{theor}} = 251.3 \pm 5.0\,\text{pb}$ [9] we can extract $\sigma_{t\bar{t}}$ using (3) taking all relevant systematic correlation between the $t\bar{t}$ and Z/γ^* cross sections into account [7]: $\sigma_{t\bar{t}} = 7.82 \pm 0.38\,(\text{stat}) \pm 0.37\,(\text{syst}) \pm 0.15\,(\text{theory})\,\text{pb}$ for the CDF topological selection and $\sigma_{t\bar{t}} = 7.32 \pm 0.36\,(\text{stat}) \pm 0.59\,(\text{syst}) \pm 0.14\,(\text{theory})\,\text{pb}$ for the CDF b-tagging selection for a 172.5 GeV top quark mass. These two measurements are further combined using a best linear unbiased estimate method to give [7]: $\sigma_{t\bar{t}} = 7.70 \pm 0.52\,\text{pb}$ for a 172.5 GeV top quark mass. The precision of the combined result is now 6.8% better than the latest theoretical computation.

4. – $t\bar{t}$ cross section in the dilepton channel

In this channel both W bosons from the decay of (anti-)top quark are decaying leptonically into one electron or one muon (or one τ lepton that further decays into an electron

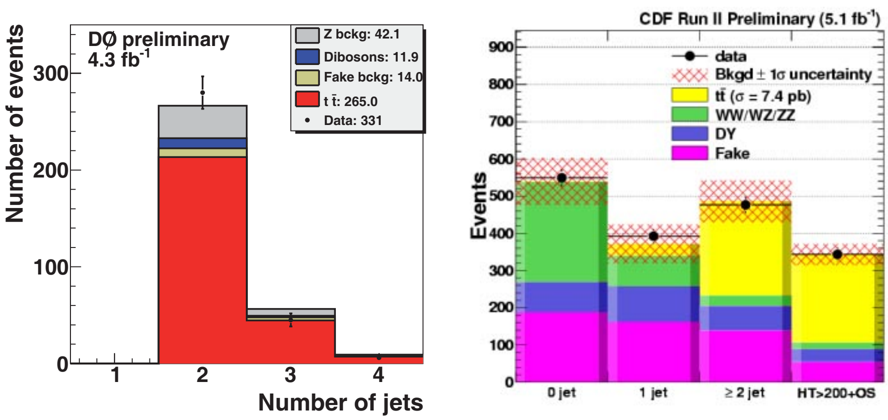

Fig. 2. – Distribution for the number of jets in DØ (left) and in CDF (right) in the dilepton channel.

or a muon). The event then contains two high-p_T isolated leptons, a large amount of $\not\!\!E_T$ and at least two jets from b-quarks. The main source of background in this channel comes from the production of electroweak bosons that decay to charged leptons. It arises from Drell-Yan processes: $Z/\gamma^* \rightarrow \ell^+\ell^-$ along with diboson production (WW, WZ and ZZ) when the bosons decays lead to at least two leptons in the final state. These backgrounds are reduced by requiring multiple jets and $\not\!\!E_T$. This event counting-based cross section measurement is performed by minimizing a likelihood function describing the probability to find the number of observed events in the data given the predicted signal and background events.

CDF latest dilepton measurement for a 172.5 GeV top quark mass using 5.1 fb^{-1} of data [10] is: $\sigma_{t\bar{t}} = 7.40 \pm 0.58$ (stat) $\pm\, 0.63$ (syst) $\pm\, 0.45$ (lumi) pb without b-tagging and $\sigma_{t\bar{t}} = 7.25 \pm 0.66$ (stat) $\pm\, 0.47$ (syst) $\pm\, 0.44$ (lumi) pb using b-tagging. DØ latest measurement from without b-tagging for a 172.5 GeV top quark mass using 5.3 fb^{-1} of data [11] is: $\sigma_{t\bar{t}} = 8.4 \pm 0.5$ (stat)$^{+0.9}_{-0.8}$ (syst) $^{+0.7}_{-0.6}$ (lumi) pb. Both measurements are now limited by the systematic uncertainties. Figure 2 shows the distributions for the number of jets in the dilepton channel at DØ (left) and CDF (right).

5. – $t\bar{t}$ cross section in the all-hadronic channel

In the all-hadronic channel, both W boson from the (anti-)top quark are decaying hadronically into two quarks. The final state consists then of at least six jets among which two of them are jets from b quark. To reduce the overwhelming QCD multijet background the use of b-tagging in this channel is essential. The purity of the sample can be further increased by means based on the kinematical and topological characteristics of the $t\bar{t}$ events. CDF is combining several kinematical jet or event variables into a neural network while DØ is using a likelihood. The event centrality, aplanarity and sphericity are used as input variables to the multivariate discriminant as well as variables like the pseudorapidity η and azimuth angle ϕ moments of a jet [12]. The multijet background determination in the all-hadronic channel relies on data. To do so, CDF evaluates the probability of tagging a jet in a sample with exactly four jets which is dominated by

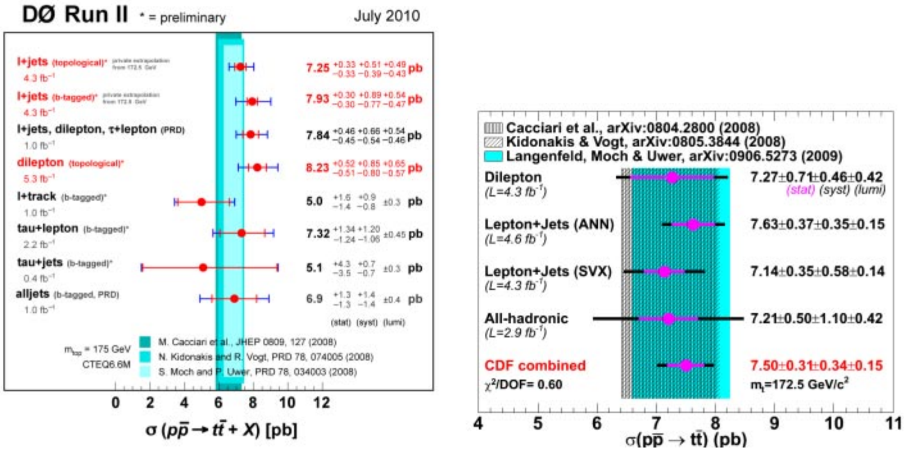

Fig. 3. – Summary of the $t\bar{t}$ cross section measurements at DØ (left) and at CDF (right).

background and uses it to predict the number of tagged events in the signal region with more than six jets. DØ creates a background sample from data by attaching low-p_T jets selected from events with six or more jets to events with four or five jets.

Using 2.9 fb^{-1}, CDF is measuring [12]: $\sigma_{t\bar{t}} = 7.2 \pm 0.5$ (stat) ± 1.0 (syst) ± 0.4 (lumi) pb for a 175 GeV top quark mass. Using 1 fb^{-1}, DØ is measuring [13]: $\sigma_{t\bar{t}} = 6.9 \pm 1.3$ (stat) $\pm$ 1.4 (syst) $\pm$ 0.4 (lumi) pb for a 175 GeV top quark mass. The uncertainty on the background modeling, on the jet energy scale and on the b-tagging efficiency dominate the systematic uncertainties on these measurements.

6. – Summary of the $t\bar{t}$ cross section measurements

CDF and DØ have measured the $t\bar{t}$ cross section in almost all possible decays channels assuming SM branching fractions, thus allowing a comparison of the results between each other and with the predictions of next-to-leading order perturbative QCD. Within uncertainties all the measured $t\bar{t}$ cross sections in the different final states agree with each other. These measurements are further combined together. Figure 3 shows all the measurements performed at the Tevatron. Work is in progress to further combine the DØ and CDF results.

7. – Top quark properties using $t\bar{t}$ cross section measurements

7.1. *Top quark mass extraction.* – The $t\bar{t}$ cross section measurement can be used to extract the top quark mass. This indirect top quark mass measurement is less sensitive to any difference between the pole mass and the mass in the MC simulation used for direct measurements. It is performed by combining the total experimental and theoretical $t\bar{t}$ cross section as a function of the top quark mass into a joint normalized likelihood function. The experimental cross section depends on the top quark mass through the selection efficiency. The so far most accurate QCD computations are used as theoretical input. Using the cross section measurements with 1 fb^{-1} of data, DØ extracts a top quark mass of [14]: $M_{\rm top} = 169.1^{+5.9}_{-5.2}$ GeV which is less precise though compatible with the world average of the direct measurements [15].

7˙2. *Cross section ratio.* – Computing the ratio of $\sigma_{t\bar{t}}$ measured in different final states or with different number of b-tagged jets allows also to test the presence of non-SM decay of the top quark, essential in case the top quark is decaying into something else than a W boson. The measurement of R_b [16] provides an example of such approach. Another example comes from the top quark decay into a charged Higgs boson ($t \to H^+b$) that can compete with the SM decay. DØ computes ratios of measured cross sections taking the correlations between channels into account. The measured values are compatible with the SM expectation of 1 [14] and limits can be set on the leptophobic or tauonic charged Higgs as well as in the minimal supersymmetric standard model or CPX scenario [17].

8. – $t\bar{t}$+jets cross section

Measuring the $t\bar{t}$+jets cross section is an important test of QCD predictions as this quantity is sensitive to NLO effects. Studying the $t\bar{t}$+jets process is also interesting since $t\bar{t}$ forward-background asymmetry is predicted to be different from the inclusive $t\bar{t}$ production and is present at LO for the $t\bar{t}$+jets process. The measurement is based on the lepton+jets selection described above. CDF [18] simultaneously fit the $t\bar{t}$+0 jet and $t\bar{t}$+jets and measures: $\sigma_{t\bar{t}+j} = 1.6 \pm 0.2$ (stat) $\pm\, 0.5$ (syst) pb for a 175 GeV top quark mass in agreement with the SM expectation. The largest systematic uncertainty on this measurement comes from the uncertainty on the jet energy scale.

9. – Differential cross section measurements

The large statistics of $t\bar{t}$ events now available at the Tevatron in the lepton+jets channel enables to study differential $t\bar{t}$ distributions. Indeed new physics like technicolor, topcolor or models with extra dimensions can distort the $t\bar{t}$ invariant mass spectrum or the transverse momentum of the top quarks in $t\bar{t}$ events compared to the SM expectations [19, 20].

CDF measures the $t\bar{t}$ differential cross section with respect to the $t\bar{t}$ invariant mass: $\mathrm{d}\sigma/\mathrm{d}M_{t\bar{t}}$ [21]. The reconstructed background subtracted $M_{t\bar{t}}$ distribution in the lepton+jets channel is corrected for experimental resolution using a regularized unfolding method. Consistency checks with the SM prediction show no evidence of non-SM physics in the $M_{t\bar{t}}$ distribution.

DØ measures the inclusive differential cross section for $p\bar{p} \to t\bar{t} + X$ as a function of the top quark p_T [22]. Based on the lepton+jets selection described above and taking into account the unreconstructed neutrino and finite experimental resolution and constraining the W boson and the top masses to fixed values a constrained kinematic fit is applied to associate the leptons and jets with the top quarks. The reconstructed p_T spectrum is corrected for experimental resolution based on a regularized unfolding method. The NLO or NNLO perturbative QCD calculations agree with the measured cross section in normalization and shape while the results from the ALPGEN [23]+PYTHIA and PYTHIA [24] describe the shape of the data distribution but not its normalization.

10. – Conclusion

The Tevatron experiments have measured the $t\bar{t}$ cross sections in all possible top decay channels. They now have in hand well-understood $t\bar{t}$ samples allowing to search for many deviations from the SM expectations. Most of the $t\bar{t}$ cross section measurements are now systematic limited. A precision of 6.5% on the $t\bar{t}$ cross section has been achieved using the

$t\bar{t}$ over Z cross section ratio. DØ and CDF will continue in the near future to scrutinize the top sector with more than $7\,\mathrm{fb}^{-1}$ of data already on tape exploring further the so far statistically limited top decay channels as well as cross section ratios and differential cross sections.

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