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Single and double top quark production at the Tevatron

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Summary. — The CDF and D0 experiments have measured single and double top quark production in $p\bar{p}$ collisions at the Tevatron at a centre-of-mass energy of 1.96 TeV. The applied methods are used to constrain properties of the top quark and to search for new physics. Several methods of signal-to-background separation and of the estimation of the background contributions are discussed. Experimental results using an integrated luminosity up to 5.3 fb^{-1} are presented.

PACS 14.65.Ha – Top quarks.

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1. – Introduction

Since the top quark was discovered by CDF and D0 at the Tevatron in 1995 [1, 2] the number of top events available for experimental studies has been increased by more than an order of magnitude. Tevatron delivered a luminosity of more than 7 fb^{-1} and up to 5.3 fb^{-1} have been used for top quark analyses in CDF and D0.

In the Standard Model (SM) top quarks can be produced through the strong or through the weak interaction. The strong interaction creates top quarks in pairs. The process is expected to be dominated by quark anti-quark annihilation with a contribution of only 15% from the gluon fusion processes. The cross-section for this process is around 7 pb. In the weak interaction top quarks can be produced singly. At the Tevatron the two mechanisms known as s -channel and the t -channel contribute to single top production with the ratio 1 : 2 to a total of about 3.5 pb.

Immediately after production top quarks decay to a W boson and a b quark with a branching fraction of nearly 100%. The decay channels of top quark pairs are thus fully specified through the W boson decay modes. For the top pair production dileptonic decays including electrons and muons allow for the highest purity, but suffer from the low branching fraction of about 5%. The semileptonic decays are considered as the golden channel due to a sizable branching fraction combined with the possibility to reach a

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reasonable signal-to-background ratio. The all-hadronic decay channel has the largest cross-section, but due to the absence of leptons it suffers from a huge background due to multijet production. Channels including τ leptons are kept separately due to the difficulties in their identification. For single top production the events are categorised by production and decay channel. So far only leptonic decays were studied.

In the following first some new results on the top quark pair production cross-section are described, followed by a selection of related and derived results. Then the observation of single top production and some related results are discussed. A discussion of measurements of the top quark mass and further top quark properties can be found in [3].

2. – Top pair production cross-section

The total cross-section of top pair production has been computed in perturbation theory using various approximations [4-8]. For a top quark pole mass of 172.5 GeV Moch and Uwer [7] find $\sigma_{t\bar{t}} = 7.46_{-0.67}^{+0.48}$ pb, based on the CTEQ6.6 [9] PDF. Experimentally it is important to measure this value in various decay channels. In addition some measurements are done requiring identified b jets while others avoid b jet identification and rely on topological selections. Most analyses use sideband data to evaluate the normalisation of the important background contributions. In the lepton plus jets channel the precision is already dominated by systematic uncertainties. In this channel production of W -bosons with additional jets yields the dominating background. Due to the difficulties in computing absolute cross-sections for this process at high accuracy it is important to take the corresponding background estimate from data.

A sizable contribution of the systematic uncertainties of these measurements also stems from the luminosity determination. To overcome this limitation CDF has measured the ratio of top quark pair production to the Z boson production cross-sections [10, 11]. In 4.6 and 4.3 fb⁻¹ of data CDF finds $\sigma_{Z \rightarrow \ell\ell} / \sigma_{t\bar{t}} = 35.7$ and $\sigma_{Z \rightarrow \ell\ell} / \sigma_{t\bar{t}} = 33.0$ for the analysis using b jet identification and the topological analysis, respectively. In the analysis using identified b jets, the background is normalised from data without identification requirement. In the topological analysis this normalisation is obtained from fits to the topological likelihood discriminant. The cross-section ratios are converted to top quark pair production cross-sections using the theoretical prediction for Z boson production. The theoretical uncertainty induced by this step is much smaller than the luminosity uncertainties and thus yield results with an uncertainty comparable to the uncertainty on the prediction for top quark pair production:

$$(1) \quad \begin{aligned} \sigma_{t\bar{t}} &= 7.14 \pm 0.35_{(\text{stat})} \pm 0.58_{(\text{syst})} \pm 0.14_{(\text{theory})} \text{ pb} \quad \text{using } b \text{ jet identification,} \\ \sigma_{t\bar{t}} &= 7.63 \pm 0.37_{(\text{stat})} \pm 0.35_{(\text{syst})} \pm 0.15_{(\text{theory})} \text{ pb} \quad \text{using topological selection.} \end{aligned}$$

D0 has recently published an analysis of the full hadronic channel. The analysis requires 6 jets two of which need to be identified as b jets. In this channel the background is dominated by multijet production from gluons and quarks other than the top quark. It is modeled from data with 4 and 5 jets by adding jets taken from 6-jet events. Only jets with lowest (and second lowest) p_T in the event are taken from 6-jet event. They must remain the lowest (or second lowest) jet in the newly constructed event. This method of event constructed has been validated by adding one jet to 4-jet events and compare them to normal 5-jet events.

The final cross-section is obtained by fitting a likelihood discriminant as observed in data to the prediction for top quark pairs from simulation and the background model

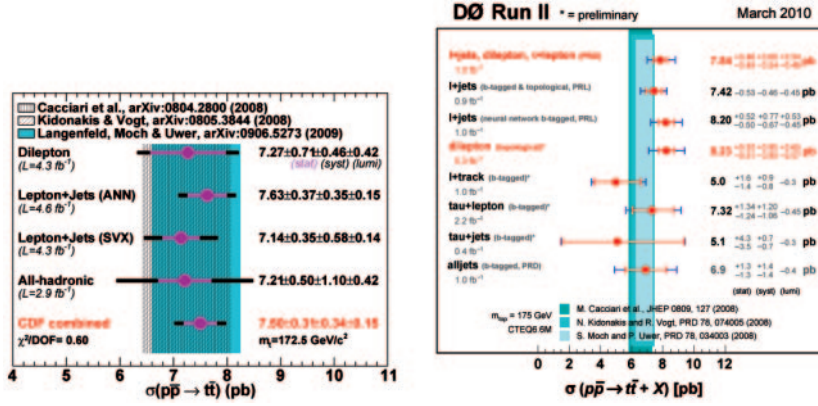


Fig. 1. – Top quark cross-section measured in various channels by CDF (left) and D0 (right).

described above. In 1.0 fb^{-1} D0 finds [12]

$$(2) \quad \sigma_{t\bar{t}} = 6.9 \pm 1.3(\text{stat}) \pm 1.4(\text{syst}) \pm 0.4(\text{lumi}) \text{ pb}.$$

Figure 1 summarises the cross-sections for top quark pair production as measured by CDF and D0 in various channels including the D0 dilepton result that was updated to 5.3 fb^{-1} since the conference [13]. All measurements agree well with the theory predictions shown as vertical bands.

2.1. Top quark mass from cross-section. – The theoretical predictions and (through the selection efficiency) also the experimental results depend on the assumed top quark mass. This can be used to determine the top quark mass in the well-defined pole mass scheme. Comparing the experimental results from three channels (ℓ +jet, the dilepton and the τ +other lepton) to the prediction from Moch and Uwer [7] D0 obtains

$$(3) \quad m_t^{\text{pole}} = 169.1_{-5.2}^{+5.9} \text{ GeV}.$$

This results has larger experimental uncertainties but is consistent with direct mass determinations for which the mass scheme, however, is not well defined.

2.2. Search for resonant top quark pair production. – In the SM no resonant top quark production is expected. However, unknown heavy resonances decaying to top pairs may add a resonant part to the SM production mechanism. Such resonant production occurs in several models of new physics: *e.g.*, for massive Z -like bosons in extended gauge theories [14], for Kaluza-Klein states of the gluon or Z boson [15,16], for axiguons [17], in Topcolor [18,19]. D0 investigated the invariant mass distribution of top pairs in up to 3.6 fb^{-1} of ℓ +jets events [20–22]. Signal simulation is created for various resonance masses between 350 and 1000 GeV. The width of the resonances was chosen to be 1.2% of their mass, which is much smaller than the detector resolution. The top pair invariant mass, $M_{t\bar{t}}$, is reconstructed directly from the reconstructed physics objects. A constrained kinematic fit is not applied. Instead the momentum of the neutrino is reconstructed from the transverse missing energy, \cancel{E}_T , which is identified with the transverse momentum of

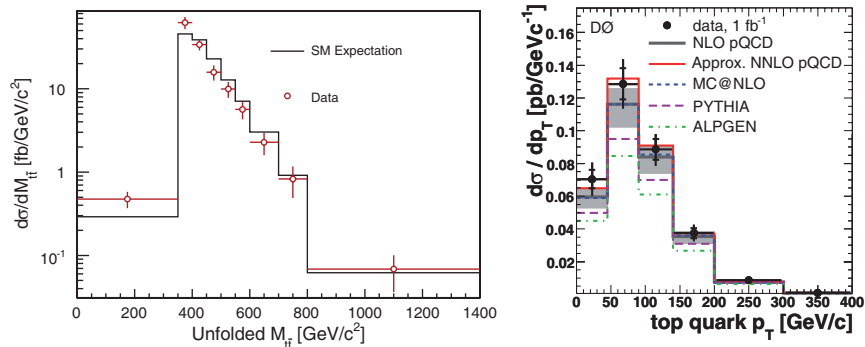


Fig. 2. – Differential cross-section of top quark pair production. Left as a function of the invariant top quark pair mass measured by CDF [24] and right as a function of the top quark transverse momentum by D0 [25].

the neutrino. The z -component is obtained by solving $M_W^2 = (p_\ell + p_\nu)^2$, where p_ℓ and p_ν are the four-momenta of the lepton and the neutrino, respectively.

As the data agrees with the SM expectations, limits on the possible contribution of resonant production $\sigma_X \mathcal{B}(X \rightarrow t\bar{t})$ are set. The benchmark model of Topcolor assisted Technicolor can be excluded for Z' masses of $M_{Z'} < 820$ GeV. A CDF study of 2.8 fb^{-1} in the all hadronic channel excludes $M_{Z'} < 805$ GeV in this model [23].

2.3. Unfolded differential cross-sections. – Besides the total cross-section in different channels, differential cross-sections can be used to validate our understanding of top quark pair production.

CDF has recently published a measurement of the unfolded differential cross-section with respect to the invariant top quark pair mass, $d\sigma_{t\bar{t}}/dM_{t\bar{t}}$ [24]. Lepton plus four or more jet events are selected with at least one identified b jet using 2.7 fb^{-1} of CDF data. The invariant mass $M_{t\bar{t}}$ is computed from the four leading jets, the lepton and the missing transverse energy. The neutrino z momentum is set to zero. The expected background is subtracted from the observed distribution, then distortions are unfolded using the singular value decomposition of the response matrix obtained from simulations. The final result is shown in fig. 2 (left). The consistency with the SM expectation is tested using Anderson-Darling statistics. The observed result has a probability of 0.28 to occur if the SM is correct, showing good agreement with the SM.

D0 has determined the unfolded differential cross-section with respect to the top quark transverse momentum, $d\sigma_{t\bar{t}}/dp_T^t$ using 1.0 fb^{-1} [25]. In lepton plus jet events including at least one identified b -jet the top quark transverse momentum is reconstructed using a kinematic fit. The fit utilises the measured momenta of the four leading jets, the charged lepton and the missing transverse energy to determine the momenta of the top quark decay products (four quarks, a charged lepton and a neutrino). Constraints on the W -boson mass and on the equality of the top and anti-top quark masses are applied. The expected background contributions are subtracted from the measured distribution. Then regularised unfolding is used to determine the final $d\sigma_{t\bar{t}}/dp_T^t$ shown in fig. 2 (right) [25]. The result is compared to prediction of perturbative QCD (in approximately NNLO) and various event generators. Perturbative QCD and MC@NLO show the best agreement, but Pythia and Alpgen reproduce the observed shape at high p_T .

3. – Single top quark production

The cross-section for single top quark production is only half that of top quark pair production. The same backgrounds as in top quark pair analyses contribute and top quark pair production itself becomes a background. Moreover, in single top quark events have a signature containing fewer jets than for top quark pairs. The signature selection requires an isolated lepton, missing transverse energy and two to four jets, at least one of which must be identified as b -jet. After this selection the signal-to-background ratio is at best 1:10. Multivariate techniques are required to further separate single top quark events from the backgrounds.

Both experiments employ multiple such methods, including boosted decision trees, various neural network methods, matrix element and likelihood techniques. The different multivariate methods are sensitive to different single top quark events. Thus a combination of the different analyses improves the significance of the result. The 5σ observations that were reported in 2009 at this conference have been published [26, 27] and combined cross-section [28] of

$$(4) \quad \sigma_t = 2.76^{+0.58}_{-0.47} \text{ pb}$$

is in good agreement with the SM expectations [29, 30].

In addition to the results obtained in the channels involving electrons or muons (marked as “Lepton+jets”), fig. 3 contains two more recent results. One by CDF [31] with 2.1 fb^{-1} omits the explicit requirement for an isolated electron or muon. This picks up events failing the lepton requirements and events with taus in the final state. No explicit tau reconstruction was done here. The second additional analysis done by D0 [32] uses boosted decision trees to explicitly reconstruct hadronic tau decays. This reconstruction is trained individually for three tau decay modes that are classified as $\tau \rightarrow \pi^\pm + \nu_\tau$, $\tau \rightarrow \rho^\pm + \nu_\tau$ and $\tau \rightarrow 3\pi^\pm + \nu_\tau (+\pi^0)$. Signal efficiencies between 59% and 76% are achieved at a background rejection rate of 98%. In 4.8 fb^{-1} D0 determines the single top cross-section in the τ +jets channel as $\sigma_t = 3.4^{+2.0}_{-1.8} \text{ pb}$.

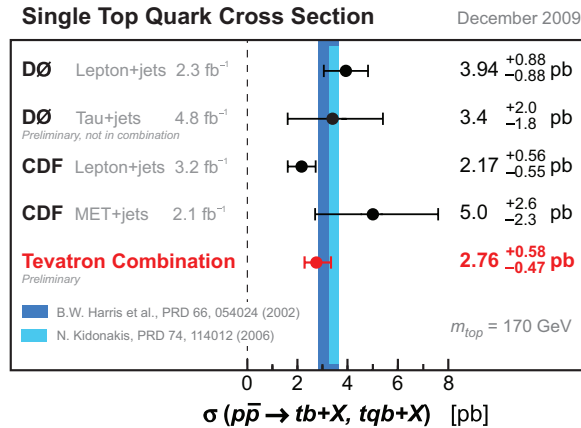


Fig. 3. – Single top quark cross-section measured by CDF and D0.

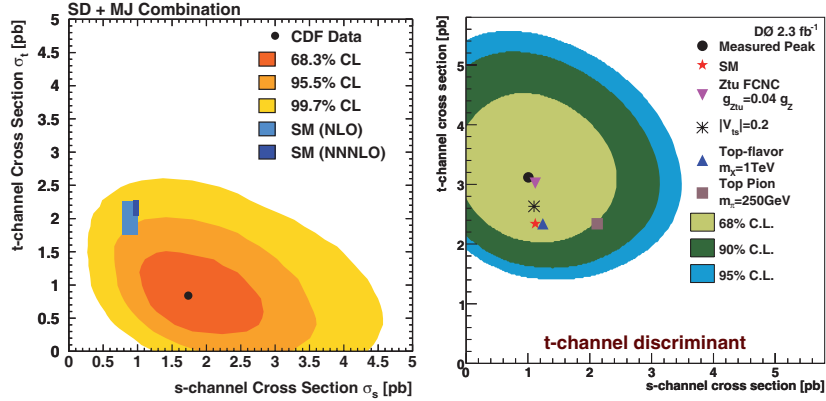


Fig. 4. – Simultaneous fit of s - and t -channel contribution to the CDF (left) and D0 (right) data [34, 35]. Results are compared to the SM expectations and some selected alternative models [36].

3.1. Determination of V_{tb} . – The single top quark production in the SM is directly proportional to the CKM-matrix element $|V_{tb}|^2$. Thus the results presented above can be easily interpreted as a measurement of $|V_{tb}|$. For the combined result CDF and D0 obtain $|V_{tb}| = 0.88 \pm 0.07$. Constraining the value to the allowed range between 0 and 1 yields a lower limit of $|V_{tb}| > 0.77$ at 95% confidence level [28]. This limit is valid independent of the number of generations, it however assumes $|V_{tb}|^2 \gg |V_{td}|^2 + |V_{ts}|^2$. This assumption is supported by measurements in top quark pairs, see *e.g.* [33].

3.2. Separation of s - and t -channel. – As explained in the introduction, single top quark production at the Tevatron actually consists of two separate processes, the s - and the t -channel. The results presented so far consider the sum of the two channels. CDF and D0 have also determined the two contributions separately [34, 35]. The two-dimensional results are shown in fig. 4. The CDF results show a deviation to the SM expectation of a little more than two standard deviations, while D0 result agrees very well with the SM. Figure 4 (right) shows the D0 results for a discriminant that was optimised to determine the t -channel cross-section. For this individual channel D0 finds in 2.3 fb^{-1}

$$(5) \quad \sigma_t^{t\text{-channel}} = 3.14_{+0.80}^{+0.94} \text{ pb}$$

with a significance of 4.8 standard deviation.

3.3. Polarisation of the top quark. – In the presence of non-SM contributions to the top quark production [36], the polarisation of the top quarks may be modified with respect to the SM expectations. CDF considered a contribution of a production through right-handed couplings, keeping the SM left-handed decay. Such a process could be implemented through a heavy right-handed W' -boson. CDF trained their likelihood discriminant separately for the the right-handed exotic and left-handed SM case. With this the corresponding two cross-sections σ_R and σ_L are measured and combined to a polarisation $\mathcal{P} = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$. In 3.2 fb^{-1} CDF obtains $\mathcal{P} = -1.0_{-0}^{+1.5}$ [37] in agreement with the pure SM production.

4. – Conclusions

The increasing Tevatron luminosity allows to measure the top quark cross-section and properties with improved precision. The integrated top quark pair production cross-section is measured in various decay channels and used to obtain the top quark pole mass. Measurements of the differential cross-section as a function of p_T or $M_{t\bar{t}}$ complement the verification of our understanding of top quark pair production and are used to search for deviations from the SM. Since the observation of single top quark production at the previous La Thuile conference, new selection channels have been added to the studies and s - and t -channel contributions have been measured separately. In addition polarisation studies have been studied in these events.

This paper only describes a small fraction of all measurements. The Tevatron experiments measure the full spectrum of top quark properties to check the production, the decay and inherent properties of the top quark against the SM expectation. So far no evidence for new physics has been found.

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