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Recent Results of Top Quark Physics from the Tevatron

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Twenty years after its discovery in 1995 by the CDF and D0 collaborations at the Tevatron proton-antiproton collider at Fermilab, the top quark still undergoes intensive studies at the Tevatron and the LHC at CERN. In this article, recent top quark physics results from CDF and D0 are reported. In particular, measurements of single top quark and double top quark production, the $t\bar{t}$ forward-backward asymmetry and the top quark mass are discussed.

1 Introduction

The heaviest known elementary particle, the top quark, has been discovered in 1995 by the CDF and D0 Collaborations in Run I of the Fermilab Tevatron proton-antiproton collider [1 2]. Due to its high mass, the top quark is believed to play a special role in electroweak symmetry breaking, and is also considered a window to new physics in many models beyond the standard model (SM). Furthermore, the top quark is the only quark that allows to study a bare quark.

The results shown in this article are based on the full Tevatron Run II data sample, collected at a collision energy of 1.96 TeV. Run II started in 2001, and ended on September 30th 2011, providing ≈ 10.5 fb^{-1} of integrated luminosity for each of the D0 and CDF experiments.

In this article, latest measurements in the single top sector, results of top antitop quark ($t\bar{t}$) production, the $t\bar{t}$ forward-backward asymmetry, and the top quark mass, are discussed.

2 Single Top

Top quark production dominantly occurs in pairs via the strong interaction, or singly via the electroweak interaction. Single top quark production happens via s-channel, t-channel and Wt-channel processes. The latter has a negligible cross section at the Tevatron.

The measurement of the single top quark production cross section is quite challenging, since the production cross section for the main background from W+jets processes is orders of magnitude larger and has a very similar final state to single top. Various multivariate analysis techniques are used, combining multiple variables into a discriminant. The first observation of single top quark production was achieved in 2009 by CDF and D0 [3 4], with s- and t-channels

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combined. The observation was based on 3.2 fb^{-1} and 2.3 fb^{-1} of data by CDF and D0, respectively. In 2011, single top t-channel production has been first observed by D0 [5] using 5.4 fb^{-1} of data. Finally, in 2014, also the s-channel production was observed by combining the CDF and D0 measurements [6], using analyses which are based on up to the full Run II data sample. Semileptonic events are considered in the analyses by both collaborations, with the addition of an analysis by CDF, where events with a missing transverse energy plus jet signature are used, adding events to the sample in which the lepton is not directly reconstructed. The combined analysis results in a cross section of $\sigma_s = 1.29^{+0.26}_{-0.24}$ pb, which deviates with more than 6.3 standard deviations (SD) from zero. Recently, a final Tevatron combination of the single top quark cross sections has been performed. This comprises a combined measurement of the t-channel cross section, $\sigma_t = 2.25^{+0.29}_{-0.31}$ pb, a two-dimensional measurement of the s- versus t-channel cross sections, and a measurement of the s+t-channel cross section, $\sigma_{s+t} = 3.30^{+0.52}_{-0.40}$ pb [7]. Using the single top cross section, the CKM matrix element $|V_{tb}|$ can be extracted. The measured value of $|V_{tb}| = 1.02^{+0.06}_{-0.05}$ corresponds to $|V_{tb}| > 0.92$ at the 95% C.L.

3 Double Top

Top quark pair production occurs via $q\bar{q}$ annihilation or gluon-gluon fusion. At the Tevatron, the former comprises approximately 85% of $t\bar{t}$ production, and the latter about 15%, which is roughly the other way round at the LHC. Besides the different collision energies, these different fractions are one of the main reasons why many measurements at the Tevatron are complementary to similar studies at the LHC.

Using the full Run II data sample of 9.7 fb^{-1}, the D0 collaboration recently performed a new measurement of the $t\bar{t}$ cross section, inclusively as well as differentially as function of the invariant $t\bar{t}$ mass, $m_{t\bar{t}}$, the rapidity of the top, $|y^{top}|$, and the transverse momentum of the top, p_T^{top} [8]. For the measurement, semileptonic events are analysed. Requiring at least four jets in the event, the inclusive cross section yields $\sigma_{t\bar{t}} = 8.0 \pm 0.7(\text{stat}) \pm 0.6(\text{syst}) \pm 0.5(\text{lumi})$ pb, in good agreement with the SM prediction. For the differential measurement, the $t\bar{t}$ event reconstruction is performed using a constrained kinematic fitter, and the distributions are corrected for detector and acceptance effects via regularized unfolding. The final distributions are defined for parton-level top quarks including off-shell effects. The unfolded $t\bar{t}$ distributions as function of $m_{t\bar{t}}$ and $|p_T^{top}|$ are shown in Figure 1 and Figure 2, respectively. The unfolded distributions are compared to approximate next-to-next-to-leading order (NNLO) calculations and different Monte Carlo generator predictions. For all measured distributions, a good agreement between data and the NNLO calculations and generator predictions can be seen.

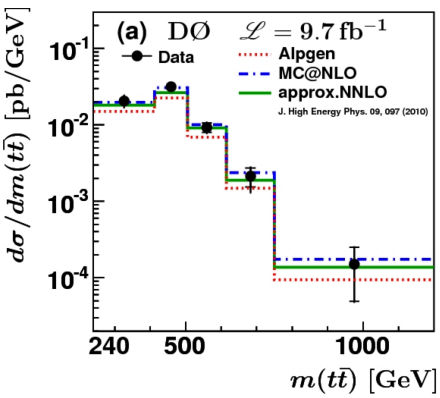

Figure 1 – Differential $t\bar{t}$ distribution as function of $m_{t\bar{t}}$ [8].

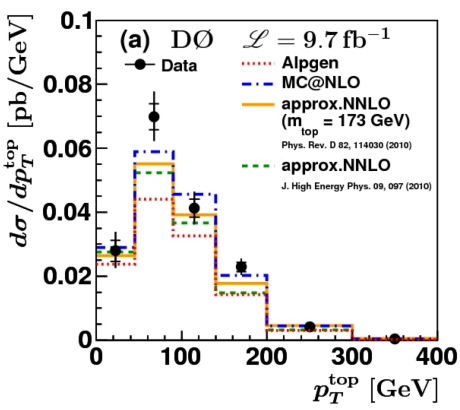

Figure 2 – Differential $t\bar{t}$ distribution as function of p_T^{top} [8].

At next-to-leading order (NLO) QCD, interference between different $q\bar{q}$ diagrams produces a $t\bar{t}$ asymmetry, causing the top quark to go more likely into the direction of the incoming quark. Various asymmetries have been studied at the Tevatron, in particular the forward-backward asymmetry $A_{FB}^{t\bar{t}} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}$, where N is the number of events with the difference in top and antitop rapidity Δy smaller or larger than zero, and the leptonic asymmetry $A_{FB}^{l} = \frac{N(q_l y_l>0)-N(q_l y_l<0)}{N(q_l y_l>0)+N(q_l y_l<0)}$, where q_l and y_l are the charge and rapidity of the lepton from the W boson decay, respectively.

Both CDF and D0 measured the leptonic and the forward-backward asymmetry in the lepton+jets and dilepton final states. In both cases the results unfolded to production level are given. Combining dileptonic and semileptonic events, D0 measures $A_{FB}^{l} = 4.7 \pm 2.3(\text{stat}) \pm 1.5(\text{syst})$ %[9 10], and CDF $A_{FB}^{l} = 9.0^{+2.8}_{-2.6}(\text{stat}+\text{syst})$ %[11 12] for the leptonic asymmetry. These results are in good agreement with the SM prediction at NLO QCD, including electroweak (EW) corrections, of $A_{FB}^{l} = 3.8 \pm 0.2$ %[14]. The measurement of A_{FB}^{l} as function of pseudorapidity is also performed, showing good agreement with Monte Carlo predictions. The measurement of $A_{FB}^{t\bar{t}}$ is done in semileptonic events in D0, resulting in $A_{FB}^{t\bar{t}} = 10.6 \pm 2.7(\text{stat}) \pm 1.3(\text{syst})$ %[15] and on dileptonic and semileptonic events in CDF, which yields $A_{FB}^{t\bar{t}} = 16.0 \pm 4.5(\text{stat}+\text{syst})$ %[16 17]. Both results are in good agreement with the NNLO SM prediction of $A_{FB}^{t\bar{t}} = 9.5 \pm 0.7$ %[13]. Recently, D0 performed a new measurement of $A_{FB}^{t\bar{t}}$ in the dileptonic final state, using the matrix element technique for the $t\bar{t}$ event reconstruction. The measured value is $A_{FB}^{t\bar{t}} = 18.0 \pm 6.1(\text{stat}) \pm 3.2(\text{syst})$%[18]. The forward-backward asymmetry has also been measured as function of $m_{t\bar{t}}$ and $|\Delta y|$. For D0, the resulting distributions are in good agreement with Monte Carlo predictions, as well as the CDF measurement.

Even though the measured $t\bar{t}$ asymmetries agree with SM predictions within errors, the experimental value is slightly higher than the prediction. While the inclusive value is compatible with SM predictions, especially the differential asymmetry measurements still do not show a clear picture: both D0 and in particular CDF measure dependencies of the asymmetry on variables, as for example the invariant $t\bar{t}$ mass, that has a somewhat higher slope than the prediction. If a non-SM contribution would enhance the measured $t\bar{t}$ asymmetry, an enhancement should also be seen for the $b\bar{b}$ asymmetry in most models. Both CDF and D0 performed measurements of the $b\bar{b}$ asymmetry. The CDF collaboration performed two measurements: an analysis of the $b\bar{b}$ asymmetry at low invariant $b\bar{b}$ mass, using a soft muon tagging technique to identify b-jets and determine their charge [19]; and an analysis of the $b\bar{b}$ asymmetry for high invariant $b\bar{b}$ mass, where the b-jets are identified using lifetime taggers and the jet charge is determined via a jet charge algorithm [20]. The D0 collaboration considered the asymmetry in the production of $B^{\pm}$ mesons, using $B^{\pm} \to J/\psi K^{\pm}$ decays [21]. All measurements are consistent with zero, not indicating any non-SM contributions.

An important property of the top quark is its mass. The mass is a free parameter in the SM. The top quark mass, together with the mass of the W boson, provide a constraint on the Higgs boson mass, and therefore provide a self-consistency check of the SM. Various methods have been employed in order to precisely measure the top quark mass, ranging from template methods to matrix element and ideogram methods. The matrix element method uses the full event kinematics, therefore being the most precise method to determine the top mass. In this method, a probability is calculated for each event, integrating over leading order matrix elements, folded with parton distribution functions and transfer functions. Recently, the D0 collaboration performed a measurement of the top quark mass in semileptonic events on the full Run II data sample of 9.7 fb^{-1}. In this analysis, the speed of the integration of the matrix element method has been improved compared to earlier measurements, allowing the integration of larger MC samples. These optimizations allowed a more precise and refined study of systematic uncertainties. To reduce the uncertainty from jet energy scale, jets from the hadronically decaying W boson are used as an in-situ constraint. The top quark mass has been measured to be $m_t = 174.98 \pm 0.58(\text{stat}+\text{JES}) \pm 0.49(\text{syst})$ GeV [22 23], where JES is the jet energy scale. Furthermore, the

D0 collaboration has released a new measurement of the top quark mass in dileptonic events, where a neutrino weighting technique has been applied in order to reconstruct the $t\bar{t}$ event. The JES uncertainty has been reduced by employing the calibration of JES on hadronically decaying W bosons in semileptonic $t\bar{t}$ events. The measure top quark mass is $m_t = 173.3 \pm 1.4(\text{stat}) \pm 0.5(\text{JES}) \pm 0.7(\text{syst})$ GeV [24]. In July 2014, a Tevatron top quark mass combination, including the new D0 top quark mass analysis in semileptonic decays, has been performed, yielding $m_t = 174.34 \pm 0.37(\text{stat}) \pm 0.52(\text{syst})$ GeV [25].

4 Summary

Even though the LHC is a top quark factory, providing huge amounts of top quark events, the analysis of Tevatron data is still valuable, providing complementary information about the heaviest known elementary particle. Many new measurements of top quark production and properties have been released recently by the CDF and D0 collaborations. Several of these are Tevatron legacies, as for example the most precise single measurement of the top quark mass, the final word from the Tevatron on the forward-backward asymmetry, and the measurement of a variety of differential $t\bar{t}$ distributions.

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