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Recent Results on Top-Quark Physics at D0

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We present the most recent measurements on top-quark physics obtained with Tevatron $p\overline{p}$ collisions recorded by the D0 experiment at $\sqrt{s} = 1.96$ TeV. The full Run II data set of 9.7 fb^1 is analyzed. Both lepton+jets and dilepton channels of top-quark pair production are used to measure the differential and inclusive cross sections, the forward-backward asymmetries, the top-quark mass, the spin correlations, and the top-quark polarization.

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1 Introduction

In 2005, when the Tevatron was the only place to find a top quark, if you you would have had to kill someone to give a talk with this title at the DPF conference. Ten years later, with huge samples of top quarks available from the Large Hadron Collider, the author was asked if he could kindly present these results from the D0 experiment, as he was going to the conference anyway. Why would anyone care about top quark measurements at D0 at this point? In fact D0 still has a number of interesting new results in top-quark physics that take advantage of the unique proton-antiproton initial state. In addition, the highly-refined D0 analysis tools and careful understanding of the veteran D0 detector allow for some very sophisticated and precise measurements of top quark properties. Thus, it was a pleasure to give this presentation.

Many results were presented at the conference, but in the interest of time and space, many of them will be tersely summarized here with references to the relevant publications. Only the newest results, especially those that are new for Summer 2015, will be discussed in detail.

As a reminder to readers, the top quark is the heaviest fundamental particle discovered so far, and the one with the largest Yukawa coupling to the Higgs boson. As a result, it is possible that it has some special role to play in electroweak symmetry breaking. It has a lifetime on the order of a yoctosecond, which means that it undergoes a weak decay before it can have any strong interactions. This allows one to measure the properties of a bare quark without messy QCD getting in the way. Because the top quark is so massive, it dominates loop diagrams that make quantum corrections to the masses of the W, Z and H bosons. Thus it plays a role in standard-model self-consistency tests, and could provide clues to the hierarchy problem and perhaps the stability of the electroweak vacuum. All of these make the study of the top quark compelling, even twenty years after it was first discovered.

The D0 experiment operated at the Fermilab Tevatron through September 2011, recording about 10 fb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The detector had a fairly small tracking volume and magnetic field, but had an excellent calorimeter and extensive muon coverage. Table 1 gives the predicted production cross sections for strongly-produced $t\bar{t}$ and electroweakly-produced single-top quarks at the Tevatron and at LHC Run 1. While the cross sections are generally much larger at the LHC, that is not the case for the s-channel single-top production in the tb mode, which is "only" a factor of five larger compared to the Tevatron. Also, at the Tevatron the $q\overline{q}$ initial state provides about 85% of the total cross section for $t\bar{t}$ production, while it is only about 15% at the LHC. This gives D0 unique access to the physics of that production mode.

	$t\bar{t}$	tb	tqb	tW
Tevatron	7.08	1.04	2.08	0.30
LHC Run 1	234	5.55	87.2	22.2

Table 1: Cross sections, in picobarns, for the production of different final states including top quarks at the Tevatron ($p\bar{p}$, $\sqrt{s} = 1.96$ TeV) and the LHC Run 1 (pp, $\sqrt{s} = 8$ TeV), assuming a top-quark mass of 173 GeV [1].

2 Production, Kinematics, Branching Ratios

One process that the Tevatron experiments have unique access to is the s-channel production of single top quarks; at the LHC, the backgrounds (from $t\bar{t}$ production) are much more significant. The rate for this process is sufficiently small that results from the full datasets of both Tevatron experiments, D0 and CDF, need to be combined to obtain a measurement with sufficient statistical significance to be called an observation of the process [2]. The cross section result, $\sigma_{s\,\mathrm{channel}} = 1.29^{+0.26}_{-0.24}$ pb, with 6.3 standard deviations significance. This measurement then allows separate estimates of the s-channel and t-channel cross sections, without any assumptions of the value of σ_s/σ_t. The results are consistent with the standard model predictions, with no indication of any other contributing process. The two cross section values then leads to a measurement of V_{tb} that makes no assumptions on the number of quark generations, unitarity, or σ_s/σ_t (but does assume standard model top decays, a pure $V-A$ interaction, and CP conservation). The result is $|V_{tb}| = 1.02^{+0.06}_{-0.05}$, or $|V_{tb}| \geq 0.92$ at 95% confidence level after applying a flat prior distribution for $|V_{tb}| < 1$.

D0 has also performed a measurement of the $t\bar{t}$ cross section as a function of various kinematic parameters such as $m_{t\bar{t}}$, $p_T(t)$ and $|y(t)|$ as a test of QCD [3]. No signs of new physics are observed.

A new preliminary measurement from D0, not yet published, gives a precise measurement of the inclusive $t\bar{t}$ cross section that makes use of both the dilepton and lepton-plus-jets channels [4]. The analysis makes heavy use of multivariate techniques, in which the numeric values of many individual observables from an event are combined to form one single quantity, and fits to distributions of those quantities from each different final state are used to obtain the cross section. The lepton plus jets channel is broken into six subsamples based on lepton type (electron or muon) and jet multiplicity (two, three or at least four jets). Each subsample gets its own boosted decision tree with gradients using about twenty kinematic variables, plus the output of a multivariate algorithm used to identify b jets. The dilepton channel is simpler. It is broken into four subsamples ($e\mu$ plus one jet, $e\mu$ plus at least two jets, ee plus at least two jets and $\mu\mu$ plus at least two jets), and the b-tag variable of the leading jet is the only one needed for the fit. Some representative distributions from

Final state	Measured cross section (pb)
Lepton + jets	7.63 ± 0.14 (stat) ± 0.59 (syst)
Dilepton	7.60 ± 0.34 (stat) ± 0.59 (syst)
Combined	7.73 ± 0.13 (stat) ± 0.55 (syst)

Table 2: Results from the inclusive $t\bar{t}$ cross section measurement

the analysis are shown in Figure 1. The cross section is obtained from a simultaneous log-likelihood fit template fit across all samples, using systematic uncertainties as nuisance parameters. The profiling of systematic uncertainties reduces them by cross-calibration (for those that are uncorrelated). Careful attention is paid to correlations amongst systematic uncertainties in the different subsamples. The leading systematic uncertainties are from signal modeling, especially hadronization.

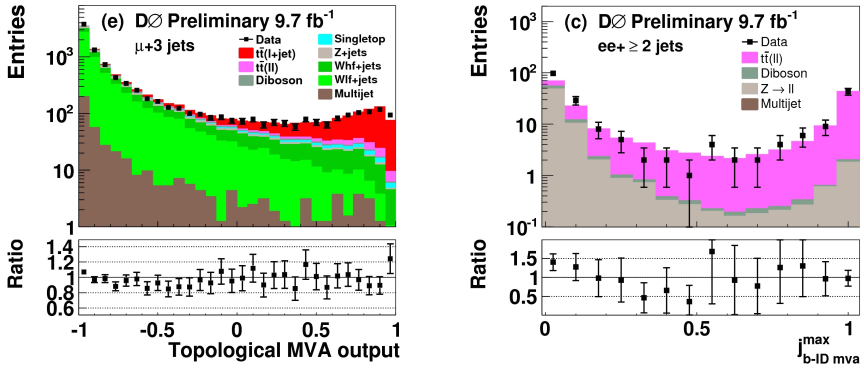

Figure 1: Representative distributions from the inclusive $t\bar{t}$ cross section measurement. Left: Output of the boosted decision tree with gradients for the μ plus three jets channel. Right: b-tag discrimination variable for the leading jet in the ee plus at least two jets channel. In both cases the colored histograms indicate the contributions from different physics proccesses.

The results for the analysis are given in Table 2. The cross sections are evaluated under the assumption of $m_t = 172.5$ GeV. But one can also use the cross section measurement to estimate the top-quark pole mass. This approach to the mass measurement avoids interpretation issues related to the definition of the quark mass. The result is illustrated in Figure 2, where the pole-mass dependence of this measurement and of the cross section are displayed. The result, $m_t = 169.5^{+3.3}_{-3.4}$ GeV, is the most precise pole-mass determination performed at the Tevatron.

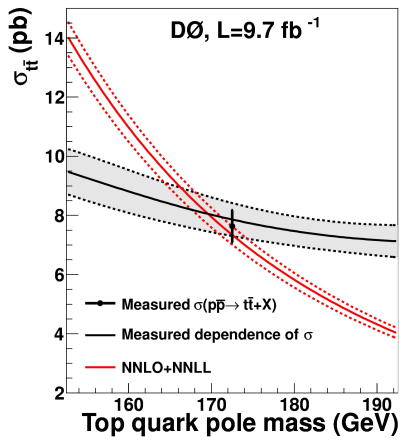

Figure 2: The measured $t\bar{t}$ production cross section dependence on the top quark mass compared to the one provided by a next-to-next-to leading order perturbative QCD calculation. [5]

3 Top mass

The most precise single measurement of the top-quark mass in the world (at this moment) uses the matrix-element method in lepton plus jets events [6]. It provides a simultaneous measurement of the top mass and a calibration factor for the jet-energy scale that is derived by constraining the hadronic W decay in the $t\bar{t}$ events to the known value of the W mass. The result is $m_t = 174.98 \pm 0.58$ (stat) ± 0.49 (syst) GeV, or $m_t = 174.98 \pm 0.76$ GeV. The publications referenced have very detailed information about the method itself and various cross checks.

D0 has also recently performed a measurement of the top-quark mass using dilepton events; a paper for publication was submitted shortly after the conference [7]. The measurement uses the neutrino weighting method, in which an integration over the phase space of the two neutrino rapidities is done on an event-by-event basis, and then a weight is calculated based on the consistency of the expected missing energy for a given mass value with the observed missing energy. A key advance compared to previous results using the dilepton final state is the transfer of the jet-energy scale and its uncertainty from the lepton-plus-jets mass measeasurement to this analysis. This measurement then becomes statistics limited, and thus much effort has gone into reducing statistical uncertainties. These efforts reduce the statistical component of the uncertainty by 25% compared to the previous form of the analysis. Using 558 events, a value of $m_t = 173.32 \pm 1.36$ (stat) $\pm$ 0.85 (syst) GeV, or $m_t = 173.32 \pm 1.60$ GeV is obtained. This result, with 0.92% precision, is consistent with the world average value, and the 0.49% systematic uncertainty is the smallest of any top-mass measure-

ment in the dilepton channel, making it competitive with results from the LHC.

4 Asymmetries and Polarizations

Due to interference terms that arise at next to leading order in QCD, $t\bar{t}$ pairs produced from $q\bar{q}$ interactions have a forward-backward asymmetry in the direction of the resulting quarks; the t tends to follow the direction of the q and the $\bar{t}$ the direction of the $\bar{q}$. This asymmetry, defined as

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}, \tag{1}$$

where $\Delta y = y_t - y_{\bar{t}}$, the rapidity difference between the top quark and antiquark, is predicted to be about 10% [5]. The Tevatron has unique access to this quantity as most of the $t\bar{t}$ pairs are produced in $q\bar{q}$ interactions, which is not the case at the LHC. The $t\bar{t}$ forward-backward asymmetry has been a topic of great interest for some years, as an anomalously large result could be an indicator of new physics, and some early measurements of this quantity using the amount of Tevatron data that was available at the time were in fact quite large.

D0 has now made several measurements of A_{FB} using the full Tevatron dataset. A measurement with the lepton plus jets final state was completed about a year ago [8]. Compared to the previous measurement in this final state, this one expanded the phase space used by including events with only three jets in the final state, and did a careful two-dimensional unfolding to parton level as a function of both Δy and different kinematic variables. The result, $A_{FB} = (10.6 \pm 3.0)\%$, agrees with the standard model prediction within uncertainties. The asymmetry shows a stronger dependence on $m_{t\bar{t}}$ and $|\Delta y|$ than predicted, but not in a statistically significant way. A measuerment of the forward-backward asymmetry for the leptons in the same lepton plus jets events also yielded a result consistent with the standard model prediction [9].

A new measurement of A_{FB} using dilepton events was available for this conference; the result has since been published [10]. The analysis actually measures the production asymmetry simultaneously with the polarization of the top quark, making this the first measurement ever of top polarization at the Tevatron. The measurement is a novel application of the matrix-element technique. A full reconstruction of the event kinematics is performed in a probabilistic fashion, and then a likelihood per event for the most probable kinematic value is made for both the asymmetry and the lepton decay angle with respect to the beam axis in the $t\bar{t}$ rest frame. The resulting distributions of the kinematic quantities, summed over all events and corrected for background contributions, is shown in Figure 3. After an appropriate calibration of the method, the relevant quantities can be extracted from the distributions. The systematic uncertainties are dominated by those involved in modeling the $t\bar{t}$ signal, in particular hadronization and showering, and also the calibration of the method.

The results of the measurement are shown in Figure 4. Without constraining either the asymmetry or the polarization, the results are

$$A_{FB} = (15.0 \pm 6.4 \pm 4.9)\% \quad (2)$$
$$\kappa P = (7.2 \pm 10.5 \pm 4.2)\%, \quad (3)$$

where the first uncertainty is statistical and the second is systematic, and $\kappa \simeq 1.0$ is the spin analyzing power of the lepton. If one of the quantities is constrained to its standard-model value, the result for the other quantity is

$$A_{FB} = (17.5 \pm 5.6 \pm 3.1)\% \quad (4)$$
$$\kappa P = (11.3 \pm 9.1 \pm 1.9)\%. \quad (5)$$

The latter result for A_{FB} is combined with that from the lepton plus jets measurement to obtain the final D0 measurement of this quantity, $A_{FB} = (11.8 \pm 2.5 \pm 1.3)\%$. The complete set of A_{FB} measurements from D0 and CDF are shown in Figure 5. As can be seen, there is a reasonable agreement between the results from the two experiments, and between the experiments and predictions from theory.

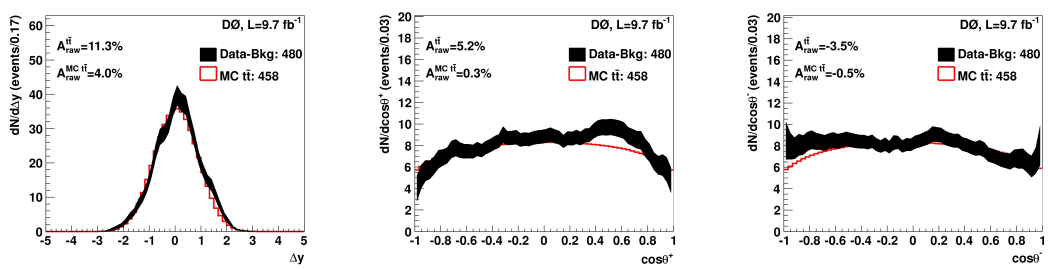

Figure 3: Estimated distribution of $\Delta y_{t\bar{t}}$ (left), $\cos\theta^+$ (center) and $\cos\theta^-$ (right) observables in dilepton events after subtracting the expected background contributions. The background-subtracted data asymmetries and the Monte Carlo asymmetries extracted from these distributions are also reported. These raw asymmetries need to be corrected for calibration effects to retrieve the parton-level asymmetries.

5 D0 top physics in the LHC era

Even with the onslaught of data from the LHC, top physics at D0 is still quite interesting. The maturity of the experiment makes some very sophisticated measurements possible, as the detector is very well-modeled and the datasets are well-understood. This allows for significant creativity in data analyses, as exemplified by the fact that the systematics-limited top mass measurements are quite competitive with those from

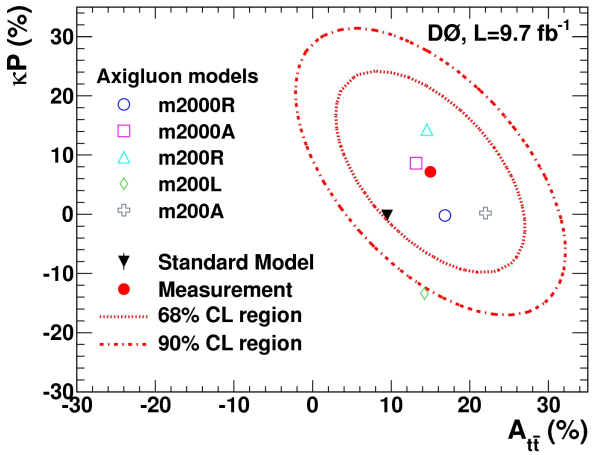

Figure 4: Two dimensional visualization of the A_{FB} and κP measurements and comparison with benchmark axigluon models. See Ref. [10] for more details about those models.

the LHC; one of them is currently the most precise single measurement in the world. In addition, the complementarity of the initial state ($p\overline{p}$ instead of pp) provides unique opportunities to search for new physics. The $t\bar{t}$ production asymmetry cannot be explored nearly as well at the LHC, and the measurement of the s-channel single-top production is very difficult there. After twenty years of top physics, the LHC experiments have much to learn from the Tevatron experience. The last few remaining D0 top-physics measurements should become available in the coming months, completing a very successful physics program.

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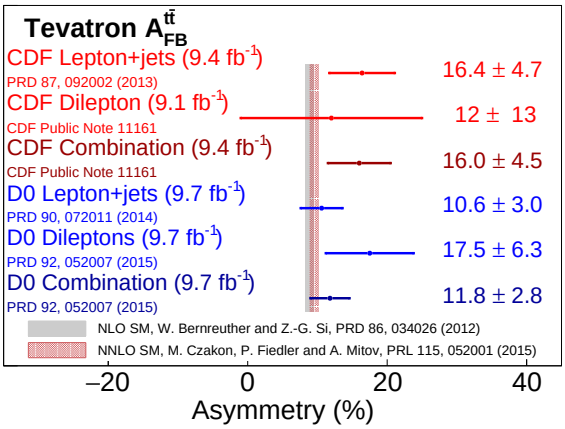

Figure 5: Summary of A_{FB} measurements at the Tevatron.

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