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Top properties from D0

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Summary. — We review recent measurements of top quark properties by the D0 Collaboration. Namely, a measurement of the helicity of W bosons produced in top quark decays, and a measurement of anomalous top quark couplings which builds upon it, an extraction of the top quark's width based on the previous single-top production cross section and $B(t \to Wb)/B(t \to Wq)$ measurements, and a direct measurement of the mass difference between top quarks and antiquarks.

PACS 14.65.Ha – Top quarks.

1. – Introduction

The heaviest of all elementary quanta in the standard model of particle physics (SM), the top quark, was discovered in 1995 by the CDF and D0 Collaborations at the Fermilab Tevatron Collider [1]. The discovery was of the main production mechanism, pair production through the strong interaction. The alternative production mechanism, single top production through the electroweak interaction, was harder to detect. Clear evidence for this production was presented last year by the CDF and D0 Collaborations [2].

The strong pair-production mechanism produces more top quarks, and is thus the primary channel for measuring top properties. However, the electroweak production mechanism offers complementary information, and recent D0 measurements combine both.

We present a model-independent measurement of the helicity of W bosons produced in top quark pair decays, and a measurement of anomalous top quark couplings, that was done primarily using single top production and includes a combination of the two measurements to yield stronger constraints. Similarly, a measurement of $B(t \to Wb)/B(t \to Wq)$ is combined with the first evidence for single top production to extract the top quark's width. Finally, we present a direct measurement of the mass difference between top quarks and antiquarks.

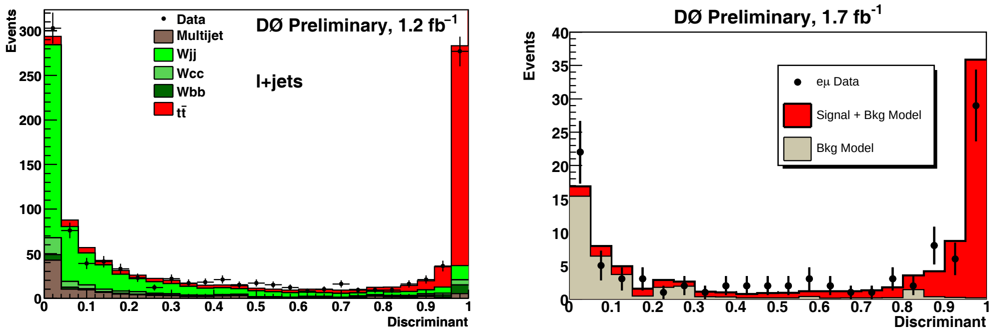

Fig. 1. – Fitted sample compositions from ref. [4].

2. – A model-independent measurement of W boson helicity in top quark decays

The SM predicts that $B(t \to bW) \approx 100\%$. Breaking this down by the W boson's helicity eigenvalues, the SM predictions are $f_+ = 0.1\%$, $f_0 = 69.6\%$, and $f_- = 1 - f_+ - f_0 = 30.3\%$ [3], which are the fractions of right-handed, longitudinally polarized and left-handed W bosons produced, respectively. We report preliminary results from a simultaneous measurement of f_+ and f_0 by the D0 Collaboration [4], that provide a model-independent test of the SM predictions.

We select events from the "lepton+jets" channel, in which one of two W bosons produced in the top pair decay decays hadronically, and the other W boson decays into an electron or muon and a neutrino, by requiring ≥ 4 jets with transverse momentum $p_T > 20\,\text{GeV}$, and an isolated electron or muon of $p_T > 20\,\text{GeV}$ and absolute pseudorapidity $|\eta| < 1.1(\text{e})$ or $2.0(\mu)$. We also require that the missing transverse energy $\not{E}_\text{T} > 20\,\text{GeV}$, and that it is not along the azimuth of the lepton. We also select events in the $e\mu$ channel, requiring ≥ 2 jets and that the leptons are isolated and have opposite electric charge. The compositions of the selected samples are shown in fig. 1, where the sample components with a lepton from W decay were modeled using Monte Carlo simulation [5, 6] and normalized using discriminants based on kinematic and b-quark identification variables, while the fake lepton components were modeled using auxiliary data samples.

We distinguish between helicity states by reconstructing the angle between the up-type decay product and the incoming top quark in the W boson's rest frame, θ^*(see fig. 2). In the lepton+jets channel we do so using a kinematic fitter which varies the four-momenta of the detected objects within their experimental resolutions and minimizes

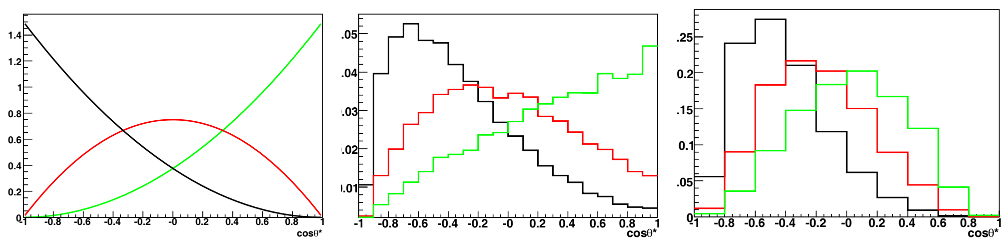

Fig. 2. – (Colour on-line) $\cos\theta^*$ distributions for left-handed (black), longitudinal (red), and right-handed (green) W bosons, shown at parton level (left), and after reconstruction in the lepton+jets (middle) and $e\mu$ (right) channels.

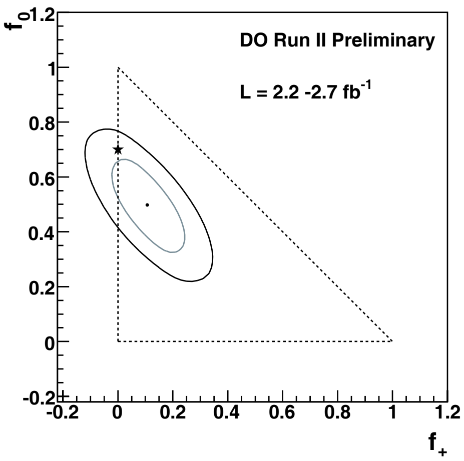

Fig. 3. – Fitted W helicity fractions [4]. The ellipses are the 68% and 95% CL contours, the triangle borders the physically allowed region, and the star marks the SM values.

a χ^2 statistic within the constraints $M_W = 80.4\,\text{GeV}$ and $m_t = 172.5\,\text{GeV}$. In the $e\mu$ channel we sample the possible resolution effects, analytically find the $t\bar{t}$ kinematics at each sampling point, and average the resulting θ^* values.

Combining with the results from ref. [7], we find using 2.2–2.7 fb^{-1} of D0 data that $f_0 = 0.490 \pm 0.106(\text{stat.}) \pm 0.085(\text{syst.})$ and $f_+ = 0.110 \pm 0.059(\text{stat.}) \pm 0.052(\text{syst.})$ (see fig. 3). We note that the results from the two channels are only consistent at the 1.6% level.

3. – Measurement of anomalous top quark couplings

Within the SM, the dominant coupling of the top quark is to the bottom quark and W boson (Wtb) and has the form $V - A$. We look for departures from the SM form for the Wtb coupling that would indicate new physics. Chen, Larios, and Yuan [8] suggested to combine the measured W helicity fractions with the single-top production rates in the s and t channels to fully specify the Wtb vertex. The D0 Collaboration published a variation on this idea [9] as follows.

We start with the most general CP-conserving Wtb vertex up to mass dimension 5:

$$(1)\quad L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b}\gamma^\mu \left(f_1^L P_L + f_1^R P_R\right) t - \frac{g}{\sqrt{2}M_W} \partial_\nu W_\mu^- \bar{b}\sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R\right) t + \text{h.c.},$$

where M_W is the mass of the W boson, P_L and P_R are the left-handed and right-handed projection operators. In the SM the parameters are: $f_1^L = 1$, and $f_2^L = f_1^R = f_2^R = 0$.

This measurement is based on a previous single-top production measurement [10] which analyzed only 1 fb^{-1} of data. To compensate for the limited statistical strength, the following assumptions are used when measuring the anomalous top quark couplings:

– the couplings constants are real, *i.e.* the interaction is CP conserving,

– the Wtb vertex dominates single top production and decay,

– only one non-SM coupling is considered at a time.

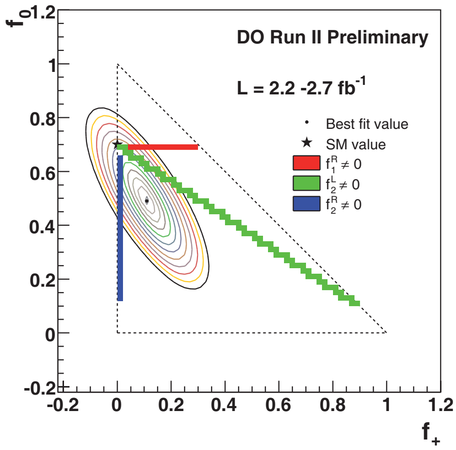

Fig. 4. – Dependence of W helicity fractions on anomalous top quark coupling [9].

This yields three scenarios: only f_1^L and f_1^R are non-zero, only f_1^L and f_2^L are non-zero, and only f_1^L and f_2^R are non-zero. In the first scenario the two contributions interfere, and this is taken into account.

The W boson helicity fractions, and through them angular distributions in the decays, are modified by anomalous top quark coupling, as demonstrated in fig. 4. We repeat the W boson helicity measurement, but with the fit extracting f_1^L and the new physics coupling (f_1^R, f_2^L, or f_2^R) instead of f_0 and f_+.

The event selection follows that of the single-top production measurement [10] with the additional requirement that either two or three jets are selected, which removes any overlap with the event sample used in the W boson helicity measurement. We then train boosted decision trees to distinguish between the single top quark signal and background as in ref. [10], but rather than assume SM single top production, we set both f_1^L and the new physics coupling (f_1^R, f_2^L, or f_2^R) to 1. In addition to the 49 variables used in ref. [10], we use the lepton p_T which helps distinguish between the signal scenarios.

For each scenario the results are combined using a Bayesian technique, yielding the limits and posterior probability density functions (PDFs) shown in fig. 5.

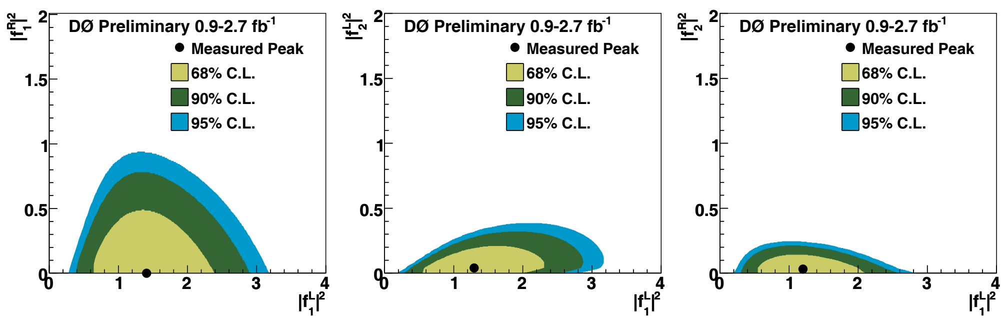

Fig. 5. – Posterior probability density functions for the Wtb couplings in the three scenarios described in the text.

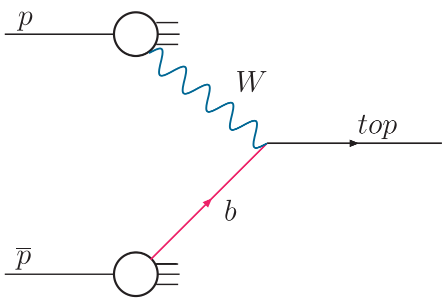

Fig. 6. – Representative diagram for Wb fusion.

4. – Extraction of the top quark width

In the standard model the lifetime of the top quark is short enough that it does not create any long-lived hadrons that can be detected as displaced vertices. Its inverse([1]), the top width Γ_t can be measured directly [11], but such measurements are limited by jet energy resolutions. We extract the top width more accurately, but indirectly, from the partial decay width $\Gamma(t \to Wb)$ and the branching fraction $B(t \to bW)$.

Following suggestion in ref. [12], we extract the width of the top quark indirectly by combining the cross section for the single-top t-channel ($p\bar{p} \to tqb + X$) [13], which is proportional to the partial width $\Gamma(t \to Wb)$, with the ratio of branching fractions

$$R_b = \frac{B(t \to bW)}{B(t \to qW)}\,. \tag{2}$$

We assume that $B(t \to qW) = 1$, and take $B(t \to bW)$ to be equal to the value we previously measured for R_b [14] with $m_t = 170\,\text{GeV}$, which is $R_b = 0.962^{+0.068}_{-0.066}(\text{stat.})^{+0.064}_{-0.052}(\text{syst.})$.

We further assume that single-top production and decays are kinematically similar to those in the SM, including:

- the Wb fusion production mechanism (see fig. 6) dominates. In particular: production via flavor changing neutral currents is negligible.
- $|V_{td}|$ and $|V_{ts}|$ are small.

In the SM, all these assumptions are supported by data, and they may also hold in certain models of new physics such as those containing a fourth generation of quarks.

Since Wtb effects top quark decay, and not only its production, we reinterpret the t-channel production cross section measurement [10] as a measurement of an effective cross section $\sigma B = \sigma_{tbqX} \cdot B(t \to bW) = 3.14^{+0.94}_{-0.80}\,\text{pb}$. Then

$$\Gamma(t \to Wb) = \frac{\sigma B}{B(t \to bW)} \frac{B(t \to bW)_{\text{SM}}}{\sigma_{tbqX,\text{SM}}}\,, \tag{3}$$

([1]) In natural units, with $\hbar = c = 1$.

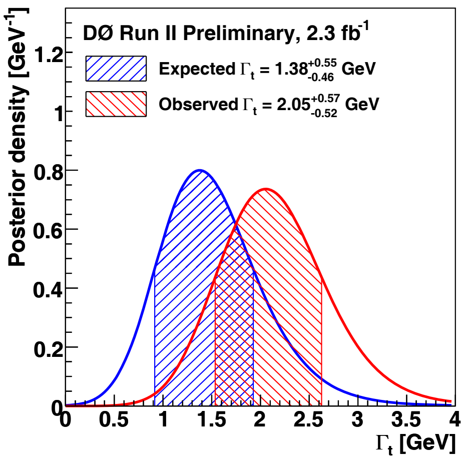

Fig. 7. – Results of top width extraction. The hatched areas represent one standard deviation around the peaks.

where the SM proportionality constant between the top partial width and the single-top production cross section, $\frac{B(t \to bW)_{\mathrm{SM}}}{\sigma_{tbqX,\mathrm{SM}}}$, is taken from a pure NLO QCD calculation. And finally,

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to bW)} = \frac{\sigma B}{B(t \to bW)^2} \frac{B(t \to bW)_{\mathrm{SM}}}{\sigma_{tbqX,\mathrm{SM}}} . \tag{4}$$

We repeat the t-channel production cross section measurement [13], but instead of extracting the production cross section, we extract the top width through eq. (4). The prior assumed for Γ_t is flat. In doing this, we take into account correlation between systematic effects common to both measurements. In particular, those on the modeling of top quark pair production, on backgrounds that do not contain top quarks and are taken from MC, on detector modeling, on the normalization of backgrounds to data, and on the performance of the b-tagging algorithm used. We find the posterior PDFs shown in fig. 7, *i.e.* a top quark lifetime of $\tau_t = (3.2^{+1.1}_{-0.7}) \cdot 10^{-25}$ s.

5. – Direct measurement of the mass difference between top and antitop quarks

From the CPT theorem [15] we expect particle and antiparticle masses to be the same in any local Lorentz-invariant quantum field theory. Testing this prediction in the quark sector is difficult, as the strong interaction binds the quarks before they decays. The top quark presents a unique opportunity to test the equality of quark and antiquark masses, as [16] its lifetime is shorter than the time scale for the QCD binding processes $\tau_t \approx 3 \times 10^{-25}\,\mathrm{s} < \frac{1}{\Lambda_{\mathrm{QCD}}} \approx 3 \times 10^{-24}\,\mathrm{s}$.

The D0 Collaboration published a direct measurement of the mass difference between top and antitop quarks [17]. The measurement is a variation of a previous analysis that measured the top quark mass (assuming $m_t = m_{\bar{t}}$) using the matrix element technique in the lepton+jets channel with $\approx 1\,\mathrm{fb}^{-1}$ of D0 data [18]. This measurement and the matrix element technique are described in detail elsewhere in these proceedings [19].

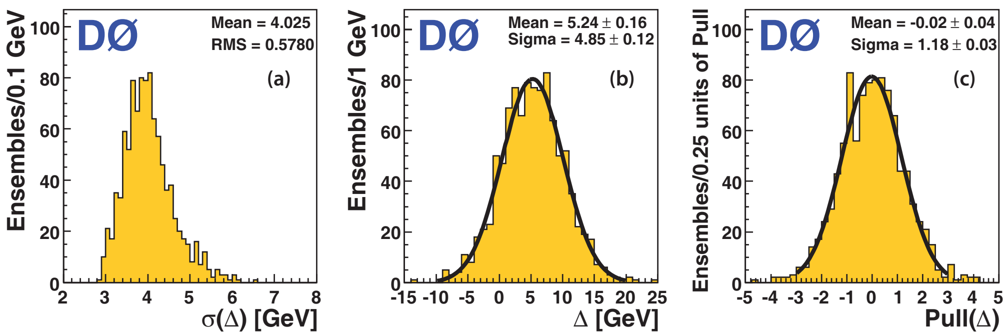

Fig. 8. – Distributions from an ensemble test generated with $(m_t, m_{\bar{t}}) = (170, 165)$ GeV and consisting of 1000 pseudo experiments with data-like composition (PYTHIA $t\bar{t}$ with ALPGEN W+jets). The histograms from left to right are: (a) expected uncertainty of the extracted mass difference, (b) extracted mass difference, and (c) pull for the extracted mass difference. Only the distributions for the e+jets channel are shown.

We separate the top quark from the top antiquark by the charge of the lepton. The polarity of D0 detector's solenoid and toroid magnets is routinely reversed, which greatly reduces any lepton-charge dependence in the reconstruction. However, the detector response to jets does depend on the charges. Specifically, K^+ and K^- interact with matter differently, which leads to the jet energy scale for jets arising from a b quark ("b jets") differing from that for $\bar{b}$ jets. These matter-antimatter differences are included in the GEANT-based [20] simulation of the D0 detector. Studies of this difference in the simulation and in D0 data find this difference to be small, and its effect is included in the systematic uncertainties.

To modify the mass measurement into a measurement of m_t and $m_{\bar{t}}$, we introduced the mass difference, $\Delta = m_t - m_{\bar{t}}$, into the matrix elements; into the PYTHIA MC generator [6], which we modified to generate events with $m_t \neq m_{\bar{t}}$; and into the acceptance, which is taken from the MC. We then perform a two-dimensional maximal-likelihood fit in m_t and $m_{\bar{t}}$ (or equivalently, in Δ and M_{sum}), and integrate the results over M_{sum} (or Δ) to obtain a one dimensional likelihood in Δ (or M_{sum}). The mass measurement used an additional fit variable—the overall jet energy scale. Here we fix its value to the one measured in the mass measurement.

Approximations made in formulating the likelihood can bias the final result. This is accounted for by comparing the measured and input values of Δ and M_{sum} in ensembles of pseudo experiments. From the ensembles we calibrate the measured values and their uncertainties, as shown in fig. 8 for an ensemble with particular Δ and M_{sum}, and in fig. 9 for all ensembles.

The resulting two-dimensional likelihoods are shown in fig. 10. From these we extract the results: $\Delta = 0.33 \pm 5.03$ GeV in the e+jets channel, and $\Delta = 6.74 \pm 4.71$ GeV in the μ+jets channel. Finally, we combine them to find $\Delta = 3.8 \pm 3.7$ GeV, which is consistent with $\Delta = 0$ as predicted from the CPT theorem.

6. – Conclusions and outlook

Recent D0 measurements of top quark properties utilize both strong and electroweak top quark production, and often gain from combining both into joint analyses. We

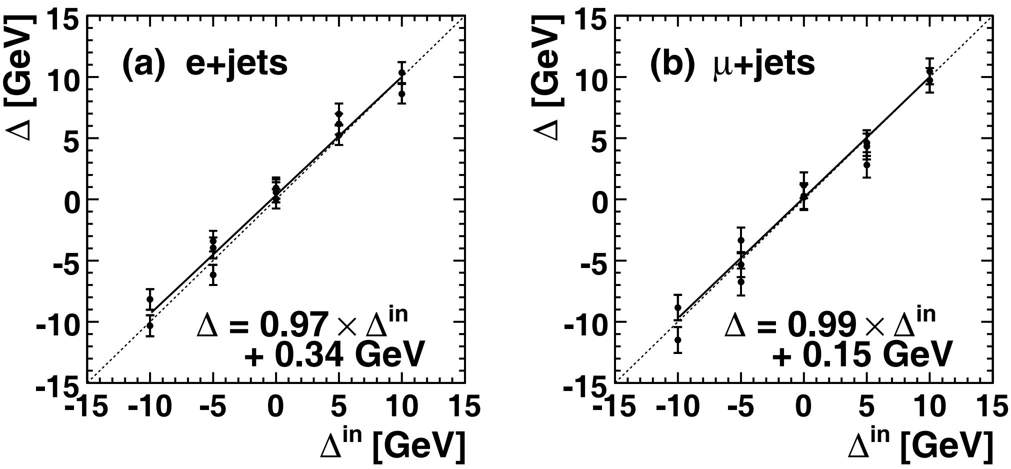

Fig. 9. – Values of the measured mean Δ from ensembles of pseudo experiments as a function of the generated mass difference (Δ^{in}), parametrized by straight lines for (a) e+jets and (b) μ+jets MC events. Results from ensembles with same Δ^{in} but different M_{sum} are shown. Dotted lines represent complete equality between measured and input values.

reported: a measurement of W helicity in top pair decays that finds $f_0 = 0.490 \pm 0.106(\text{stat.}) \pm 0.085(\text{syst.})$ and $f_+ = 0.110 \pm 0.059(\text{stat.}) \pm 0.052(\text{syst.})$, constraints on anomalous top quark couplings, a top quark width of $2.05^{+0.57}_{-0.52}$ GeV that was extracted from measurements of the partial decay width and the dominant branching fraction, and the first direct measurement of a quark–antiquark mass difference that finds for top quarks $\Delta = 3.8 \pm 3.7$ GeV. Several new results are expected this summer.

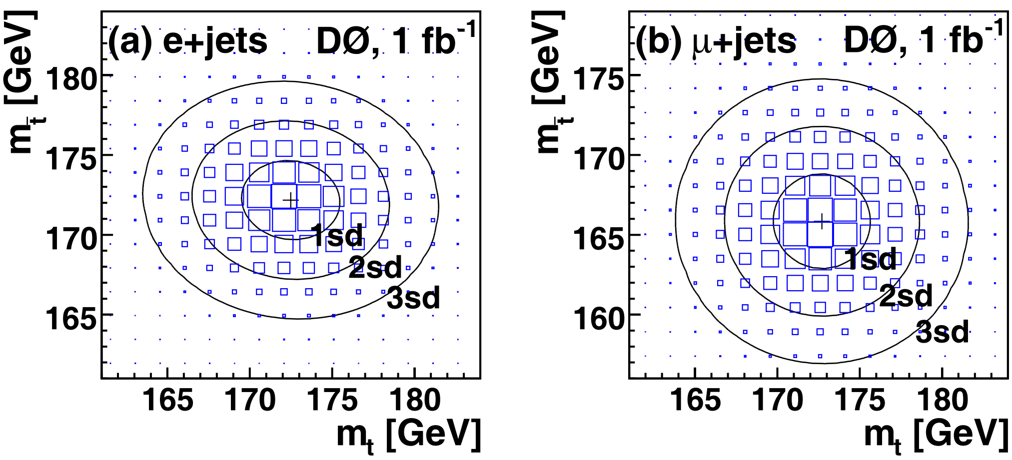

Fig. 10. – Likelihoods for the top quark and antiquark masses for (a) e+jets and (b) μ+jets data. The boxes have areas proportional to the value of the likelihood evaluated at their center. The black curves trace contours of equal probability.

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