Top Physics at the Tevatron

J. Cochran
Iowa State University

Since the observation of the top quark in 1995, considerable progress has been made by the CDF and D0 collaborations in measuring top quark production and decay properties. The combined top quark mass from both experiments is $m_t = 174.3 \pm 5.1$ GeV$/c^2$. With this determination of the top quark mass, the remaining properties of the top quark are predicted by the standard model, allowing for many new tests for physics beyond the standard model. Current and future investigations are discussed.

I. INTRODUCTION

Since the discovery of the top quark in the spring of 1995 [1,2], the DØ and CDF collaborations have continued exploring the top sector by refining their measurements of the $t\bar{t}$ production cross section ($\sigma_{t\bar{t}}$) and top mass (m_t), and by initiating other measurements such as V_{tb}, $p_T(t)$, and $m_{t\bar{t}}$. The results presented here are based on the full Tevatron Run I (1992-1996) data sets of 110 and 125 pb^{-1} for CDF and DØ, respectively. Assuming a production cross section of ~ 5 pb, these luminosities translate into 550 and 625 $t\bar{t}$ pairs produced during Run I in the CDF and DØ detectors. The Tevatron has a bunch crossing rate of 286,000 Hz with 1-2 inelastic (hard) $p\bar{p}$ collisions/crossing, resulting in tremendously large initial event samples from which these top events must be selected. It should also be noted that these top samples are quite small when compared with those expected from multijet and W boson production (the primary backgrounds to top production).

At the Tevatron energy of $\sqrt{s} = 1.8$ TeV, top quarks are produced primarily in pairs through the annihilation processes $q\bar{q} \to t\bar{t}$ (90%) and $gg \to t\bar{t}$ (10%). Top quarks should also be produced singly via electroweak processes such as W-gluon fusion. As a consequence of its very large mass, the lifetime of the top quark is very short ($\approx 10^{-24}$ seconds). And since the QCD hadronization time is of the order of $\approx 10^{-23}$ seconds, the top quark does not live long enough to hadronize but instead decays as a free quark.

Within the standard model (SM), the top decays almost exclusively into Wb ($|V_{tb}| \approx 1$). The final states are therefore classified primarily by the decay of the W bosons, and in some cases are further categorized by the presence or absence of a soft lepton in the b-jet. These primary channels are the "dilepton" (both Ws decay leptonically), the "lepton+jets" (one W decays leptonically, one W decays hadronically), and the "all jets" (both Ws decay hadronically). A special note should be made about the τ channels. Since $W \to \tau\nu_\tau \to e/\mu\nu_{e/\mu}\nu_\tau$ decays are essentially indistinguishable from $W \to e/\mu\nu_{e/\mu}$ decays, both experiments include such events as part of the leptonic W decays in the dilepton or lepton+jets channels, as appropriate. Other channels are the $\ell\tau$ (e or μ plus a hadronically decaying τ) dilepton channel (CDF), and the $e\nu$ channel (DØ), which requires one electron, two or more jets, and very large missing E_T and $e\nu$ transverse mass.

II. CROSS SECTIONS

Measurement of the top quark production cross section $\sigma_{t\bar{t}}$ is of interest primarily because it provides a good test of QCD calculations [3–7]. Additionally, any discrepancies with SM expectations, for one or more channels, could be indicative of new physics.

As noted above, top channels are classified primarily by the decay of the W bosons and the lepton+jets channels are further divided according to how the rejection against the W+jets background is achieved: (1) a displaced vertex tag used only by CDF, (2) a soft-lepton-tag used by both DØ and CDF, and (3) a topological discrimator used only by DØ. Approaches (1) and (2) attempt to identify whether there are any b-quarks in the event (backgrounds will only rarely contain b-quarks). Approach (3) exploits the differences between the topology of the signal and that of the background.

As shown in Table I, CDF and DØ both observe a clear excess of events over the expected background in the dilepton, lepton+jets, and all-jets channels [8,9]. The two experiments have followed somewhat different strategies in defining their event samples, with CDF taking advantage of their silicon vertex detector to identify b-quarks, while DØ makes greater use of kinematic variables to reduce backgrounds.

Using as input the luminosity, the acceptances, the $t\bar{t}$ decay branching fractions for the various channels, and the background-subtracted event yields, both experiments determined the $t\bar{t}$ production cross section [10,11]. These cross sections are given in Table I and are in good agreement with the theoretical expectations [3,4,6,7] for a top mass of 175 GeV/c^2.

III. MASS MEASUREMENTS

As described below, measurements of the top quark mass, m_t, have been made in the lepton+jets, dilepton, and all-jets channels. Due to the possible presence or absence of neutrinos, the procedure varies for these three cases.

For the lepton+jets channel, there are 6 particles in the final state (18 observables), one unknown ($p_z(\nu)$) and three constraints: $m(\ell\nu) = m_W$, $m(j_h j_h) = m_W$, and $m(j_h j_h b_h) = m(b_\ell \ell\nu) = m(\text{top})$, where j_h is a jet from the hadronically decaying W, b_h is the b jet associated with the hadronically decaying W, and b_ℓ is the b jet associated with the leptonically decaying W. This gives a doubly over-constrained problem (2C fit). This situation is complicated by the fact that it is often not possible to distinguish both b jets in every event, and by the presence of initial and final state radiation. The presence of backgrounds further complicate the picture.

The basic procedure is as follows: Select a sample of $t\bar{t}$ events and for each candidate make a measurement of some quantity (X) which is a function of the true top mass. This distribution contains both signal and background. From $t\bar{t}$ Monte Carlo determine the shape of X for many choices of m_t. From Monte Carlo and data determine the shape of X for background. These signal and background distributions are then combined and compared with that obtained from the candidate sample. A likelihood fit then determines the signal+background set (and thus which top mass) best matches the candidate sample.

Both experiments follow this same general procedure, they differ only in the method by which the candidate sample is selected. Events are required to have one charged lepton (e or μ), four or more jets, and missing E_T. And when it is available, both experiments make use of information that identifies or "tags" certain jets as b-quark jets. Since the original discovery, both experiments have modified the event selection criteria used in the mass analyses to minimize any mass biases inherent in the selection.

CDF selects lepton+jets events with four or more jets and classifies them into four independent sub-categories based on any b-tagging information. Each of the four sub samples: (1) events with two SVX b-tagged jets, (2) events with a

TABLE I. The observed number of events and expected backgrounds for the top decay channels studied by the CDF and DØ experiments. The $e\nu$ channel requires a large transverse mass and is sensitive to τ, dilepton, and lepton+jets events that fail the standard cuts. The event selection criteria and background techniques are described in Refs. [8-11]

	DØ			CDF		
	Data	Background	$\sigma(t\bar{t})$	Data	Background	$\sigma(t\bar{t})$
Dilepton	5	1.4 ± 0.4	5.0 ± 3.3	9	2.4 ± 0.5	$8.2^{+4.4}_{-3.4}$
Single Lepton (vertex b-tag)	-	-	-	34	9.2 ± 1.5	$6.2^{+2.1}_{-1.7}$
Single Lepton (lepton b-tag)	11	2.5 ± 0.5	8.3 ± 3.5	40	22.6 ± 2.8	$9.2^{+4.3}_{-3.6}$
Single Lepton (topological)	19	8.7 ± 1.7	4.1 ± 2.1	-	-	-
All Jets	41	24.8 ± 2.4	7.1 ± 3.2	187	142 ± 12	$10.1^{+4.5}_{-3.6}$
$e\nu$	4	1.2 ± 0.4	9.6 ± 7.5	-	-	-
$e\tau$, $\mu\tau$	-	-		4	2.0 ± 0.4	$10.2^{+16.3}_{-10.2}$

single SVX b-tagged jet, (3) events with a soft lepton tag, and (4) untagged events, are analyzed separately as the signal to background ratio and the mass resolutions for them are different. The analysis consists of solving a system of constrained equations, the constraints of which are: the two tops must have the same mass and the two jets plus the $\ell\nu$ must equal the W mass. In this process jet energies and momenta are allowed to fluctuate within the detector resolution. The final fit is a combination of the four subsample likelihood fits shown in fig. 1: $m_t = 175.9 \pm 4.8(\mathrm{stat}) \pm 5.3(\mathrm{sys})$ GeV/c^2 [12].

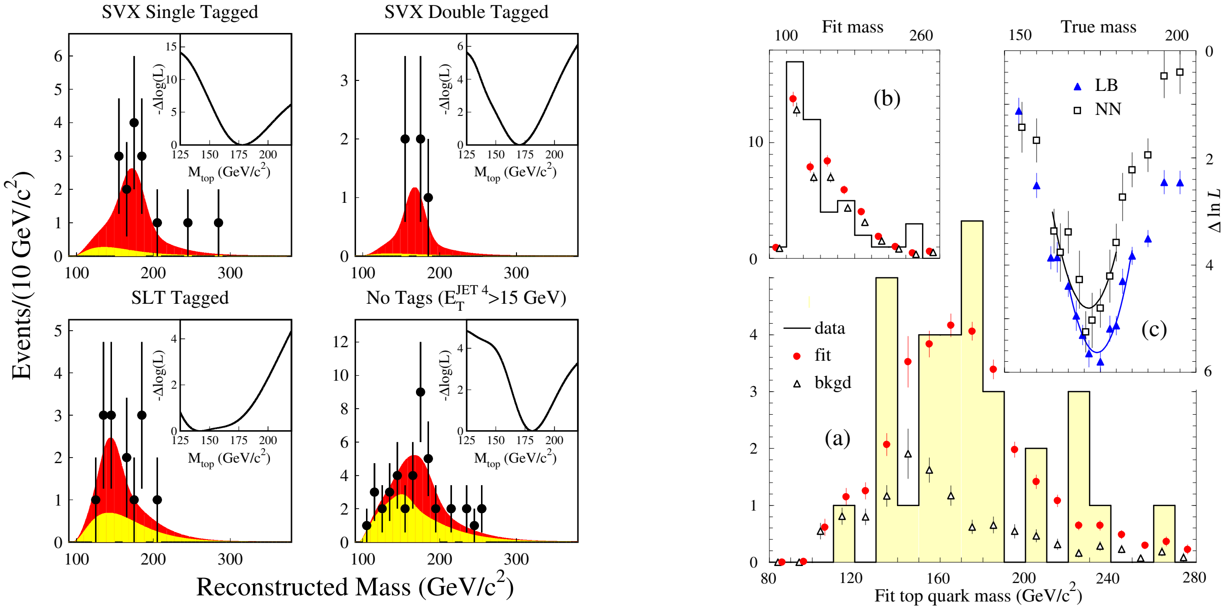

FIG. 1. **Left:** Reconstructed mass distributions for the CDF lepton+jets candidate events. The inset shows negative of the Log likelihood L versus true top quark mass m_t. **Right:** Events per bin versus $m_{\rm fit}$ for DØ events (a) passing or (b) failing the LB cut. (c) negative of Log likelihood L versus top quark mass m_t.

DØ introduced four variables [13] that individually provide some separation between signal and background. These variables are combined into a multivariate discriminant ($0 \leq \mathcal{D} \leq 1$) [1], which provides a measure of the probability for an event being $t\bar{t}$ signal and gives excellent separation between signal and background with essentially no correlation with top mass. All the events are then reconstructed using the four leading jets with a 2C constrained fit to the top quark pair hypothesis, and a value of $m_{\rm fit}$ is obtained for each event. Then, for events with 80 GeV/c^2 $\leq m_{\rm fit} \leq$ 280 GeV/c^2, the data, expected signal, and expected background are binned in the $(\mathcal{D}, m_{\rm fit})$ plane and a fit is made of the signal+background models to the data. In this way, for each top mass for which Monte Carlo events have been generated, a likelihood value is determined. The sample is coarsely divided into signal-rich and background-rich regions by means of the so called LB cut [13]. This cut is passed if an event has a soft μ tag or if $\mathcal{D} \geq 0.43$ and $H_{T2}(\equiv H_T - E_T^{\rm jet1}) \geq 90$ GeV (H_T is the scalar sum of the E_T of all jets in the event). The number of events per bin are shown in Figs 1(a) and (b) for events passing and failing the LB cut. The likelihood values as a function of m_t for both methods are shown in Fig. 1(c). Fits to these values yield: $m_t = 174.0 \pm 5.6(\mathrm{stat})$ GeV$/c^2$ (LB) and $m_t = 171.3 \pm 6.0(\mathrm{stat})$ GeV$/c^2$ (NN) with a systematic error of 5.5 GeV$/c^2$. Combining the two results, taking into account the correlation (88%), DØ determines the top quark mass in the lepton+jets channels to be $m_t = 173.3 \pm 5.6(\mathrm{stat}) \pm 5.5(\mathrm{sys})$ GeV$/c^2$.

[1] DØ uses two methods (LB and NN) to obtain the discriminant values $\mathcal{D}$. For the LB ("low bias") method, the discriminant is constructed from a log likelihood function ($\mathcal{L}$) based on the relative densities of the signal and background samples as a function of these four variables. Alternatively, the NN ("Neural Network") method inputs these four variables into an artificial neural network (trained on samples of signal and background) and outputs the discriminant.

For the dilepton channels there are again 6 particles in the final state, and 18 quantities completely specify an event, but only 14 quantities are measured: 2 charged leptons, 2 jets, $p_x(\nu)+p_x(\bar{\nu})$, and $p_y(\nu)+p_y(\bar{\nu})$. And there are again 3 constraints: $m(\ell^+\nu)=m_W$, $m(\ell^-\bar{\nu})=m_W$, and $m(b\ell^+\nu)=m(\bar{b}\ell^-\bar{\nu})=m(\text{top})$. This is an underconstrained problem. The experiments have therefore resorted to using mass estimators other than the reconstructed mass. In principle, any quantity that is correlated with the top quark mass can be used as an estimator. In all cases, the same technique that was used for the lepton+jets mass analyses is used to calculate a top quark mass likelihood in the dilepton mass analysis.

Both experiments supply the missing constraint in the problem by assuming a top quark mass and then reconstructing the event for each such assumed mass [14]. Based on the reconstructed final state a weight is computed which characterizes how likely it occurs in $t\bar{t}$ decay for the assumed mass. Two algorithms are used to determine the weight. The matrix element weighting (MWT) method used only by DØ uses the proton structure functions and the probability density function for the energy of the charged lepton in the rest frame of the top quark (an extension of Ref. [15]). The neutrino weighting method (νWT) used by both DØ and CDF assigns the weight based on the available phase space for the neutrinos, consistent with the measured $\not\!\!E_T$. A maximum likelihood fit is performed to the shape of the weight curve summed over all 6 dilepton mass events digitized into 5 bins (which are normalized to unity) using Monte Carlo derived probability density functions for signal and background. The DØ results for the two analyses are in excellent agreement : $m_t = 168.2 \pm 12.4(\text{stat})$ GeV/c^2 (DØ MWT) and $m_t = 170.0 \pm 14.8(\text{stat})$ GeV/c^2 (DØ νWT) with a systematic uncertainty of 3.6 GeV/c^2. By combining the two results, taking into account the correlations (77%), DØ determines the top quark mass in the dilepton channels to be $m_t = 168.4 \pm 12.3(\text{stat}) \pm 3.6(\text{sys})$ GeV/c^2 The CDF result is found to be in good agreement: $m_t = 167.4 \pm 10.3(\text{stat}) \pm 4.8(\text{sys})$ GeV/c^2

CDF has also obtained a top quark mass measurement in the all jets channel [8]. The event selection for this channel consists of six or more jets, a displaced-vertex-tag, plus further event shape requirements. This measurement uses the reconstructed top quark mass based on a 3C fit to the top quark pair hypothesis as its mass estimator, with a likelihood derived using the same template method that is used for other top quark mass measurements. The result is $m_t = 186.0 \pm 10.0(\text{stat}) \pm 5.7(\text{sys})$ GeV/c^2.

All these individual mass measurements were combined, including all correlations, to obtain a final Run I Tevatron top mass:

$$m_t = 174.3 \pm 3.2(\text{stat}) \pm 4.0(\text{sys})\ \text{GeV}/c^2.$$

The χ^2 probability for this average is 75%. Note that the fractional uncertainty on the top mass is less than 3%. Run II expects a factor of 30 increase in top events. This will result in a statistical error of ≈ 0.6 GeV/c^2 . Uncertainties in Monte Carlo modelling and jet energy scale are likely to be the dominant systematic errors.

IV. TESTS OF SM PREDICTIONS

Now that the top quark mass has been determined, the remaining properties of the top quark are predicted by the standard model, opening the door for many new tests of the standard model in a new regime. These tests include the following:

- Agreement between theory and experiment for $\sigma(t\bar{t})$ for all standard model channels (CDF and DØ).
- Observation of the W in $t \to Wb$ (CDF).
- Agreement between theory and experiment for kinematic distributions (CDF and DØ).
- W polarization in top decays (CDF).
- Presence of $t\bar{t}$ spin correlations (DØ).
- Single top cross section (CDF): $\sigma < 15.4$ pb at 95% C.L.

- Measurement of V_{tb} (CDF): $|V_{tb}| = 0.99 \pm 0.15$, $|V_{tb}| > 0.76$ at 95% C.L.
- Search for rare decays (CDF): BR$(t \to Z + q) < 0.33(95\% C.L.)$, BR$(t \to \gamma + q) < 0.032(95\% C.L.)$.
- Search for top to Charged Higgs Decays (CDF and DØ).
- Constraint on the mass of the Higgs boson.

Due to space constraints only a few of these tests will be discussed below.

A. Observation of the W in $t \to W + b$

The standard model predicts that top quarks will decay almost 100% of the time via $t \to Wb$, producing final states of $WWb\bar{b}$ for top pair production. In an effort to confirm this, CDF has studied lepton+jets events that have two identified b jets [16]. Figure 2 shows the invariant mass of the two highest E_T jets that are not tagged. A clear peak is observed in the mass distribution; fitting the peak to a Breit-Wigner form yields $m_{jj} = 78.1 \pm 4.4(\mathrm{stat}) \pm 2.9(\mathrm{sys})\mathrm{GeV}/c^2$, which is in good agreement with the W boson mass. The transverse mass of the $\ell\nu$ system in these events is also consistent with W decay. Thus, the final state $WWb\bar{b}$ has been fully reconstructed and the existence of the standard model decay mode $t \to Wb$ is confirmed.

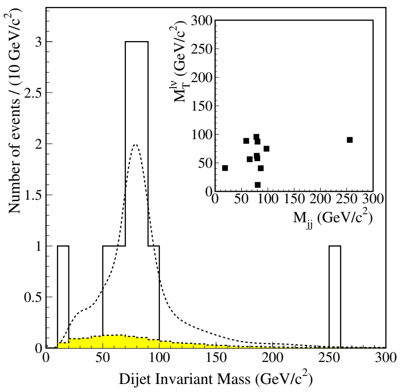

FIG. 2. Dijet invariant mass distribution for the two highest E_T untagged jets in CDF double-tagged lepton+jets events. The dashed line shows the result of fitting the mass distribution. The inset shows the correlation between the jet mass and the transverse mass for each event.

B. $t\bar{t}$ spin correlations

Quantumchromodynamics predicts that top quark pairs will be produced with significant spin correlation at the Fermilab Tevatron. The correlation is such that a significant asymmetry is expected in the number of top quark pairs produced with their spins opposed relative to their spins aligned. Since top quarks do not hadronize prior to decay, information regarding the states of relative polarization can be retrieved from the angular correlation of the decay products. If the top quark were to hadronize prior to decay, any polarization imparted at production would be diluted. Thus, apart from its intrinsic test of our understanding of top quark pair production, the observation of spin correlation in $t\bar{t}$ final states can be used to set a lower bound on the width of the top quark.

In the standard model, the angular distribution for the decay of a polarized top quark into a b-quark and a W can be written as:

$$\frac{dN}{d(\cos\theta_i)} = \frac{1}{2}(1 + \alpha_i \cos\theta_i),$$

where θ_i is the angle between the momentum vector of the final-state particle i and the direction of the projection of the spin of the top quark, all defined in the rest frame of the top quark, and α_i is a constant determined from theory, and depends on the nature of the particle i and on the mass of the top quark.

To measure the correlation between the spins of t and $\bar{t}$ requires simultaneous measurement of the decay of the two top quarks. For any two final-state particles i and j, with i originating from t and j from $\bar{t}$, the differential decay rate can be written as

$$\frac{dN}{d(\cos\theta_i)d(\cos\theta_j)} = \frac{1}{4}(1 + \kappa\cos\theta_i\cos\theta_j),$$

where κ is the spin-correlation coefficient and represents the degree to which spin correlation is present. κ is bounded between -1.0 and 1.0, with $\kappa = 0$ for uncorrelated production. DØ has a preliminary result of $\kappa > -0.2$ at the 68% C.L. from Run I data. The larger sample of dilepton events that will be available in Run II will improve this result significantly.

C. Search for top to charged Higgs Decays

The standard measurement of the inclusive $t\bar{t}$ production cross section in $p\bar{p}$ collisions, is based on the assumption that the top quark decays exclusively to a W boson and a b-quark, the branching ratio for $t \to Wb$ is taken as 1. Both experiments have investigated the possibility of the existence of a two-Higgs doublet containing a charged-Higgs pair lighter than the top quark. In such a scenario, one or both of the top quarks could decay into a charged Higgs boson and a b-quark. Assuming that this is the only alternative decay mode available to the top quark (*i.e.* $BR(t \to bW) + BR(t \to bH^+) = 1.0$, they have studied the effects this would have on the acceptance of the standard analysis in the lepton+jets final states in $p\bar{p}$ collisions. The acceptance depends on the mass of the charged Higgs boson (m_{H^+}) and the parameter $\tan(\beta)$ as well as on the mass of the top quark (m_t). The searches scan the m_{H^+} vs $\tan(\beta)$ plane, with m_t and $\sigma(t\bar{t})$ as parameters.

Based on the number of observed events, for $m_t = 175$ GeV, and various choices of $\sigma(t\bar{t})$, the 95% exclusion regions in the m_{H^+} vs $\tan(\beta)$ plane are shown in Fig. 3. Similarly, the 95% C.L. limits, for $m_{H^+} < 120$ GeV, on $BR(t \to H^+b)$ are found to be

$$BR(t \to H^+b) > 0.32 \text{ (CDF)}$$
$$BR(t \to H^+b) > 0.45 \text{ (DØ)}.$$

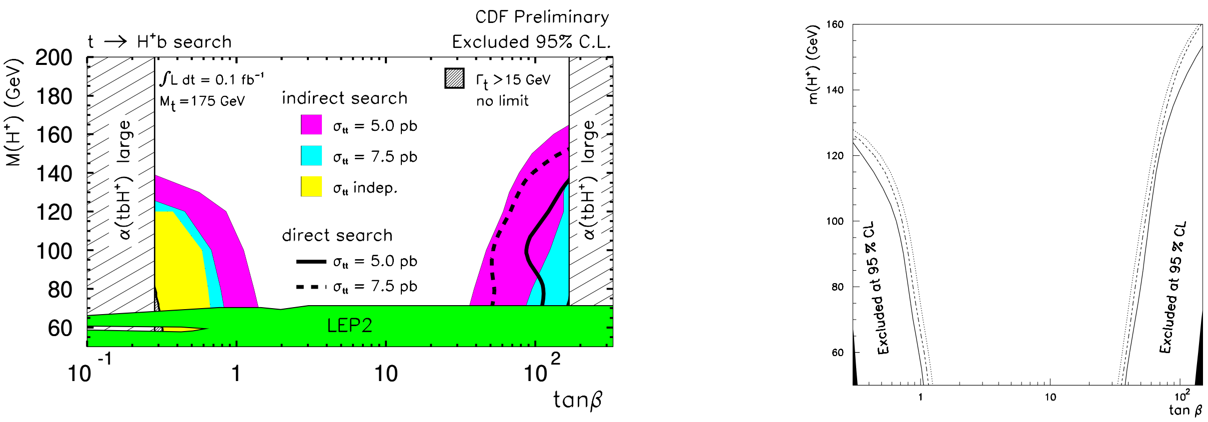

FIG. 3. The 95% CL exclusion boundaries in the $[m_{H^+}, \tan(\beta)]$ plane. **Left:** CDF, for $m_t = 175$ GeV, and value of $\sigma(t\bar{t})$ set to 5.5 pb, 7.5 pb, and independent of $\sigma(t\bar{t})$. **Right:** DØ, for $m_t = 175$ GeV, and value of $\sigma(t\bar{t})$ set to 5.5 pb (solid lines), 5.0 pb (dashed lines), and 4.5 pb (dotted lines).

V. FUTURE

Run II of the Fermilab Tevatron is slated to begin in the Spring of 2000, after the Main Ring is replaced by the Main Injector. The faster repetition rate of the Main Injector will triple the antiproton production rate, and its larger phase space acceptance will benefit both the proton and antiproton beams. A fivefold increase in luminosity is expected. A further factor of 2-3 is sought from "recycling" the antiprotons from the collider, recooling them with electrons, and storing them in a new small ring made from permanent magnets. Each experiment expects to receive $\approx 2\mathrm{fb}^{-1}$ which twenty times the current luminosity of $\approx 0.1\mathrm{fb}^{-1}$. Furthermore, an increase in the center of mass energy from 1.8 to 2.0 TeV will provide a 35% increase in the $t\bar{t}$ cross section. These conditions will produce a top yield approximately thirty times the current sample. Both detectors are being upgraded to match these new capabilities.

These large data sets will improve significantly the accuracy of all top measurements and may thereby point the way toward new physics. Estimates of the expected precision of several measurements are given in Table II [17].

TABLE II. Expected Run II precision for various top measurements.

Measurement	δm_t	$\delta\sigma(t\bar{t})$	$\delta[\sigma(\mathrm{dilep})/\sigma(\mathrm{lep+jets})]$	$\delta B(t\to Wb)$	$\delta F(t\to W_{\mathrm{long}}b)$	δV_{tb}	$B(t\to c\gamma)$	$B(t\to Zc)$
Precision	2-3 GeV	9%	12%	2.8%	5.5 %	13%	$< 2.8\times10^{-3}$	$< 1.3\times10^{-2}$

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