Fermilab FERMILAB-Conf-02/344-E January 2003

TOP STUDIES

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December 2, 2002

Abstract

The top quark, discovered in 1994 at the Tevatron, has proven a very interesting particle. Its characteristics allow both to perform stringent tests of electroweak theory, and to search for new physics through a deviation from standard model predictions for several of its peculiar properties. I will review the status of top physics and briefly describe the potential of experiments of the near future.

1 Introduction: a brief history of top physics

The first hint of the existence of the top quark can be argued to have been the detection of CP violation in the $K^\circ \bar{K}^\circ$ system in 1964: Kobayashi and Maskawa in 1973 demonstrated that three generations of quarks are needed to allow CP violation via a complex phase in the flavour matrix. However, it was only in 1977, with the discovery of the Υ states, that the top quark became a fixed thought of experimenters and theoreticians worldwide.

On the theoretical side, the renormalizability of the Standard Model (SM) demands a cancellation of triangle anomalies. The existence of a $I_3 = +\frac{1}{2}$ partner of the newborn b quark was thus direly needed for the internal consistency of the model. Moreover, an isosinglet b quark generates copious flavor-changing neutral current decays of strange and bottom hadrons, such as $b \to sl^+l^-$: none of the resulting B-hadron decays, heavily suppressed in the SM, was observed experimentally.

Additional evidence that the top quark had to complete the third generation soon came from several measurements at e^+e^- machines: first, in 1978 the PLUTO and DASP collaborations measured the leptonic width Γ_{ee} of the $\Upsilon(1s)$ meson[1], determining that the b-quark must have $Q = -\frac{1}{3}$; then in 1983 the JADE experiment measured a large forward-backward asymmetry in $e^+e^- \to b\bar{b}$ reactions[2], when none was predicted in the SM if $I^b_{3,L} = 0$. In 1987 ARGUS results suggested that the top quark mass had to be large, since the mixing parameter X_d was found to be large in the analysis of the $B^0\bar{B}^0$ system[3]. Finally, in 1990 the first precision measurements of electroweak parameters from the LEP experiments at CERN started pouring in; most notably, the precision measurements of $\Gamma(Z \to b\bar{b})$ allowed to establish that $I^b_{3,L} = -\frac{1}{2}$[4].

These and other determinations of electroweak parameters were used by theorists to produce several standard model predictions and upper limits for the top quark mass.

In the meantime, direct searches were carried out at all available experimental facilities around the world. A jump in $R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$ and/or changes in event shape were sought, along with direct evidence for T hadrons. None of the experiments found any evidence of top production, and mass limits were set at increasing M_t values, up to $M_Z/2$ (reached first by ALEPH in 1990[5]).

Hadron colliders soon joined the group and rapidly took over. The first collaboration to produce results was the UA1 experiment at the S$p\bar{p}$S ($\sqrt{s} = 630$ GeV), which sought direct evidence of top quark production in the decays of the recently discovered W bosons, $p\bar{p} \to WX \to t\bar{b}X$. In 1984 they obtained 12 $l + jj$ events on a background of 3.5, claiming discovery and quoting $M_t = 40 \pm 10$ GeV/c^2. The new particle, however, refused to show up in added statistics, and the result became $M_t > 44$ GeV/c^2 at 95% CL[6]. In 1990 UA2 improved the limit to $M_t > 69$ GeV/c^2[7], but by then eyes were already pointed at the Tevatron, where the higher center-of-mass energy promised discovery.

With the 4 pb^{-1} of data collected in 1988-89 the CDF collaboration indeed observed a very clear dilepton event, but was only able to place a 95% confidence level (CL) limit at $M_t > 77$ GeV/c^2, soon improved to $M_t > 91$ GeV/c^2[8]. The breakthrough came with the increased luminosity of Tevatron Run I in 1992, when the CDF experiment was equipped with a new silicon detector capable of identifying b-quark jets from the reconstruction of b-decay vertices. The seven candidate events identified in 19 pb^{-1} were only enough to claim a 3 σ evidence in 1994, but they allowed to measure $M_t = 174 \pm 16$ GeV/c^2[9]. Finally, in 1995 conclusive evidence was brought by both CDF and D0[10]. The quark sector of the Standard Model was now complete. Figure 1 illustrates the convergence of direct and indirect determinations of M_t in the last 15 years.

2 Intrinsic top quark properties

2.1 Top mass and width

The most important property of the top quark is its mass, which is very large when compared to all other SM fermions. The top mass is actually close to the scale of electroweak symmetry breaking: the top quark Yukawa coupling is "natural", because $y_t = \sqrt{2}\frac{M_t}{v} \sim 1$. This coincidence of scales might suggest that the top quark is actively involved in the breaking of electroweak symmetry. It must also be noted that, in the framework of minimal supersymmetric models (MSSM), a large value of M_t was actually *predicted* as far back as in 1982[11], since without a large value of M_t, radiative corrections to the mass of the lightest neutral scalar M_h would have prevented the spontaneous breaking of SU(2)xU(1) symmetry.

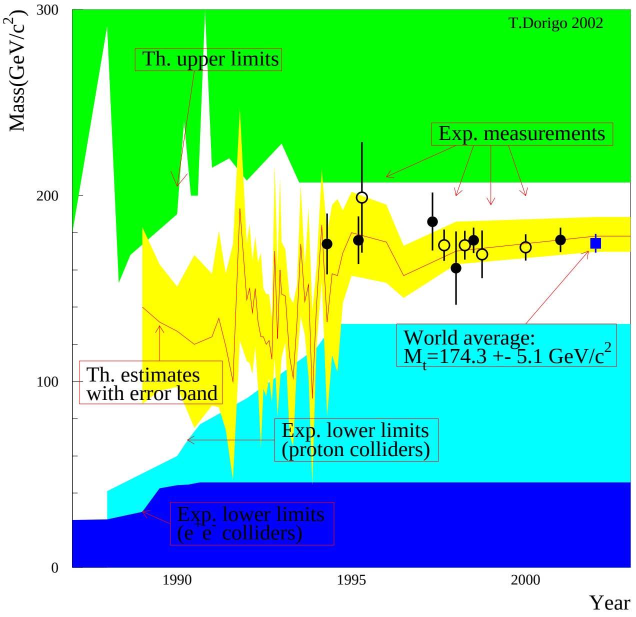

Figure 1: *A compilation of experimental and theoretical results on the top quark search. Experimental lower limits from e^+e^- and $p\bar{p}$ colliders are compared to indirect upper limits and estimates of M_t from SM fits to electroweak observables. The direct measurements by CDF (full points) and D0 (empty points) are also indicated, as well as the current world average (full square).*

In any case, M_t is a very important parameter for the tests of EW theory. Because of the quadratic dependence of the $\Delta\rho$ parameter on top mass, a precise knowledge of the latter is important for stringent consistency checks of the theory. Also, the large value of the Yukawa coupling y_t would make it advantageous to probe the $t\bar{t}h$ vertex, if the Higgs boson were found. It must finally be stressed that a precise measurement of M_t yields vital information on the mass of the Higgs boson: an uncertainty of 1 GeV$/c^2$ in the top mass yields the same amount of information on the value of M_h as an uncertainty of 7 MeV$/c^2$ on the W boson mass[12].

The large value of M_t implies that the decay time is very short: $\Gamma_t \sim M_t^3 \sim 1.5$ GeV$/c^2$. That value is one order of magnitude larger than the hadronization scale Λ_{QCD}: that implies that top quarks cannot bind to form hadrons, and they decay as free particles. The absence of top hadrons can also be inferred from the non-relativistic quark model: on one side, the mass splitting $M_{B^{**}} - M_B = 450$ MeV$/c^2$ is independent on the heavy quark mass, and must hold for T^{**} and T as well; on the other, the splitting between B^* and B depends on $1/M_Q$ and is thus expected to be smaller for top hadrons. Moreover, toponium states cannot exist, since their width ($\Gamma_{tt} \sim 2\Gamma_t \sim 3$ GeV$/c^2$) is larger than the splitting between $1S$ and $2S$ states expected from the perturbative QCD potential. All top resonances therefore merge and act coherently, and what is left in the cross section is only a broad excitation curve.

On the experimental side, several possibilities for testing production and decay properties of top quarks are granted by the large value of Γ_t and have already started to be investigated with Tevatron data. Decay products can provide information about top polarization, because the depolarization time $\tau_d \sim M_t/\Lambda^2_{QCD}$ is much longer than the lifetime. One can also study W helicity and verify the absence of $h_{W^+} = +1$ state, suppressed by the chiral factor $(M_b/M_W)^2$, and the predicted fraction of longitudinal states. It must finally be noted that a measurement of the top quark mass with unmatched precision ($\Delta M_t \sim 100$ MeV/c^2) can in principle be achieved with threshold scans at a high-energy e^+e^- collider, since Γ_t acts as an infrared cut-off in the theoretical computation of the shape of cross section at threshold, removing the influence of non-perturbative contributions.

2.2 Top decay

Since $|V_{tb}| \sim 1$ and $M_t > M_W + M_b$, the decay $t \to W^+b$ dominates. At the Tevatron, $t\bar{t}$ final states are classified according to the decay of the produced W bosons: when these both decay to quark pairs the final state is "all-hadronic" and contains nominally six jets ($B = \frac{4}{9}$); when one of them decays to $e\nu_e$ or $\mu\nu_\mu$ the "single-lepton" final state arises ($B = \frac{8}{27}$), with a $l\nu_l$+ 4 jet topology; when both W bosons decay to electron-neutrino or muon-neutrino pairs one has the "dilepton" final state ($B = \frac{4}{81}$), characterized by a $l\nu_l l'\nu_{l'}$+ 2 jet topology. $W \to \tau\nu_\tau$ decays are excluded from the above classification, since at hadron colliders it is hard to trigger on these decays and to detect τ lepton decays.

Besides the dominant channels, top quarks have been sought in the flavour-changing neutral current decays $t \to Zc(u)$ and $t \to \gamma c(u)$. In addition, in the MSSM a light charged Higgs boson can be produced in the decay $t \to H^+b$. Other supersymmetric decays of the top quark are beyond the purpose of this paper.

3 Topics in top quark physics today

3.1 Measurements of the top quark mass

All direct determinations of the top quark mass to date come from the CDF and D0 collaborations, who have measured it with many different techniques in all available final states. The single most precise determination is based on single lepton events from CDF: it is briefly described below.

Data redution proceeds by selecting events passing high-P_T electron and muon triggers. To select a W sample, charged leptons are required to have E_T (P_T)> 20 GeV(/c^2), and missing transverse energy $\not{E}_T > 20$ GeV. In addition, four hadronic jets are required; three of them must have $E_T > 15$ GeV and rapidity $|\eta| < 2.0$. From the events passing these criteria four disjoint subsets are constructed; in decreasing background content they consist of events with two jets possessing an identified secondary vertex (SVX) tag from b decay, events with one SVX tag, events with one jet containing a soft electron or muon candidate (SLT) from

b decay, and events where all four jets have $E_T > 15$ GeV. Background contaminations are mainly due to QCD $Wb\bar{b}$ and $Wc\bar{c}$ production and to fake heavy flavor signals. By keeping the four samples separated the measurement errors on M_t are minimized.

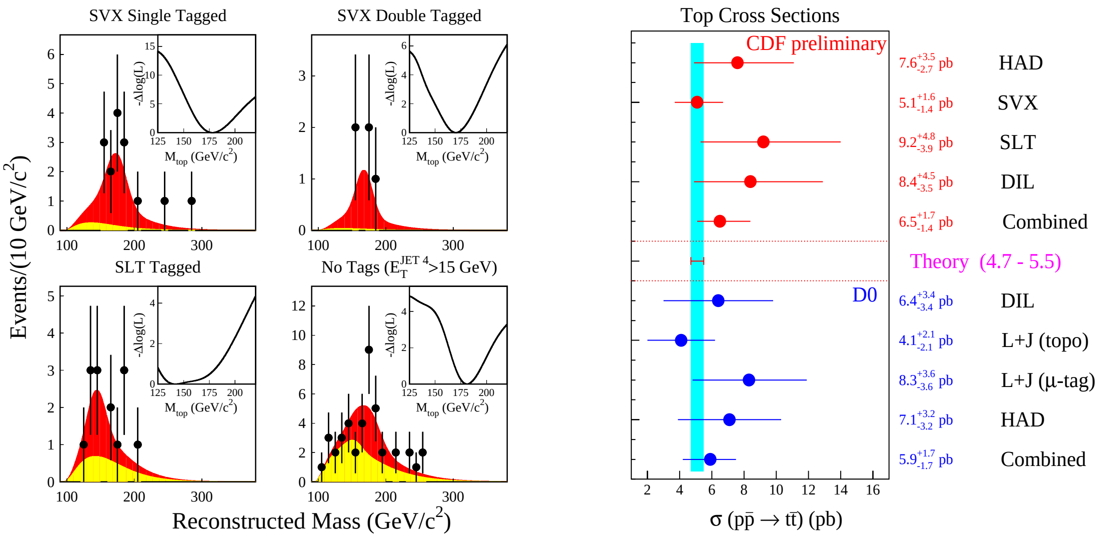

Figure 2: *Left: top mass distributions of the four subsamples of CDF data in the single lepton channel (see text); right: summary of Tevatron determinations of* $\sigma_{t\bar{t}}$.

A kinematical fit is applied to each event under the hypothesis of top decay, with the constraints that SVX- or SLT-tagged jets are assigned to b quarks, that the lepton-neutrino and jet-jet masses are compatible with M_W, and that top and antitop masses are equal. The best χ^2 solution is used. A likelihood technique determines the mass for each distribution; the four results are then combined together. The final result is $M_t = 175.9 \pm 4.8$ (stat.) ± 4.9 (syst.) GeV/c^2[13].

All CDF and D0 determinations of the top quark mass have been combined by accounting for correlated systematics. The world average value is $M_t = 174.3 \pm 3.2$(stat.) ± 4.0 (syst.) GeV/c^2[14].

3.2 Top quark production at the Tevatron

At $\sqrt{s} = 1.8$ TeV, the dominant top production process is via strong interaction, 90% of which is due to $q\bar{q}$ annihilation. Fig. 2 summarizes the Tevatron determinations of $\sigma_{t\bar{t}}$[15]. In total, the averaged CDF and D0 measurements ($\sigma_{t\bar{t}} = 6.5^{+1.7}_{-1.4}\ pb$, $M_t = 175$ GeV/c^2 (CDF), $\sigma_{t\bar{t}} = 5.7 \pm 1.6\ pb$, $M_t = 172.1$ GeV/c^2 (D0)) are in good agreement with theoretical predictions[16].

In addition to pair-produced $t\bar{t}$ pairs, single top quarks can be produced by weak interaction via a virtual W (32%) or through Wg fusion; the total is expected to be $\sigma_{tX} = 2.4\ pb$.

Single top production is interesting in its own right: a precise measurement of the cross section would provide a direct determination of $|V_{tb}|$; moreover, the process consistutes a significant background to the most promising signature of a SM Higgs ($p\bar{p} \to W^+HX \to l^+\nu b\bar{b}X$). The identification of single top production is more challenging than $t\bar{t}$ production, since there are fewer jets in the final state, and the topology is less distinctive.

CDF and D0 have both searched for $s-$ and $t-$ channel top production separately; CDF also searched for both processes together[17]. In the combined search, CDF used $W+$ jets data with at least one SVX b-tagged jet, selected with the requirement that $140 < M_{l\nu j_1} < 210$ GeV$/c^2$. The sum of leptons and jets transverse energy, $H_t = \Sigma_j E_t + P_t^l + \not{E}_T$, is very similar in both $s-$ and $t-$ channel top production, and discriminates them from the main backgrounds. A likelihood fit allows to extract the limit $\sigma_{tX} < 14$ *pb* at 95% CL. To find single top events at D0, a neural network is trained to separate the two processes from concurring backgrounds. D0 limits are $\sigma_t^s < 17$ *pb*, $\sigma_t^t < 22$ *pb* (95% CL). CDF searched separately for $s-$channel events in double SVX-tagged $W + 2$ jets data and for $t-$channel events in single SVX-tagged $W+2$ jets data. The limits extracted are $\sigma_t^s < 18$ *pb*, $\sigma_t^t < 13$ *pb* (95% CL).

3.3 Other measurements with top quarks

3.3.1 Helicity of W bosons in top decay

The SM predicts the polarization of W bosons emitted in t decay. The amplitude for positive helicity W^+ is suppressed by the chiral factor M_b^2/M_W^2. Moreover, at tree level the relative fraction of zero helicity W bosons is $\mathcal{F}_0 = \frac{M_t^2/2M_W^2}{1+M_t^2/2M_W^2} = 0.701 \pm 0.016$.

The V-A coupling at the lepton vertex induces a strong correlation between W helicity and lepton momentum. CDF used both single lepton and dilepton decays to fit the lepton P_T spectrum, obtaining $\mathcal{F}_0 = 0.91 \pm 0.37 \pm 0.13$ and $\mathcal{F}_+ = 0.11 \pm 0.15 \pm 0.06$[18], in good agreement with SM predictions.

3.3.2 Rare decays and FCNC

Flavour-changing neutral currents in top decay are exceptionally small in the SM: the decays $t \to Zc(u)$, $t \to \gamma c(u)$ are predicted to have branching fractions $B < 10^{-10}$. The CDF collaboration searched these processes by looking for $t\bar{t}$ pairs undergoing mixed decay (one standard and one FCNC)[19]. In the $t \to \gamma q$ search, both leptonic ($\gamma l \not{E}_T jj$) and hadronic signatures ($\gamma \geq 4j$, where a jet is SVX-tagged) were accepted. One $\mu\gamma$ event was observed, with large $E_t^\gamma = 88$ GeV, but not inconsistent with the hypothesis $t\bar{t} \to WbWb\gamma$. The extracted limit is $B < 0.032$ at 95% CL. In the $t \to Zq$ search, leptonic Z decays with four accompanying jets were sought. One event passes the cuts, with an expected background of 0.6 events. The limit obtained is $B < 0.33$ at 95% CL.

Constraints on FCNC couplings of the top quark can be obtained also from the search of single top production at LEP II[20]. Limits on the cross section for $e^+e^- \to \gamma, Z^* \to t\bar{q}$

can be translated into constraints to the top quark FCNC branching ratios. The ALEPH collaboration found 58 events compatible with the decay in 411 pb^{-1} of data taken at $\sqrt{s} = 189 - 202$ GeV, with an expected background of 50.3, and extracted the limit $B(t \to Zq) < 0.17$ at 95% CL. OPAL found 85 events in 600.1 pb^{-1} of data at energies up to $\sqrt{s} = 209$ GeV, when 84.1 were expected. The resulting limit was $B(t \to Zq) < 0.137$ at 95% CL.

A search for anomalous top quark production mediated by FCNC via a γut coupling was also performed by both ZEUS and H1[21]. H1 sought $ep \to etX$ events with both leptonic and hadronic W final states in 115.2 pb^{-1} of data; 5 events were found, with 1.8 expected from SM sources. They set the limit $k_{tu\gamma} < 0.22$ at 95% CL. ZEUS analysed 130 pb^{-1} of data in a similar way. They set a limit of $k_{tu\gamma} < 0.19$ at 95% CL. Fig. 3 compares the HERA, LEP II, and Tevatron limits on these quantities.

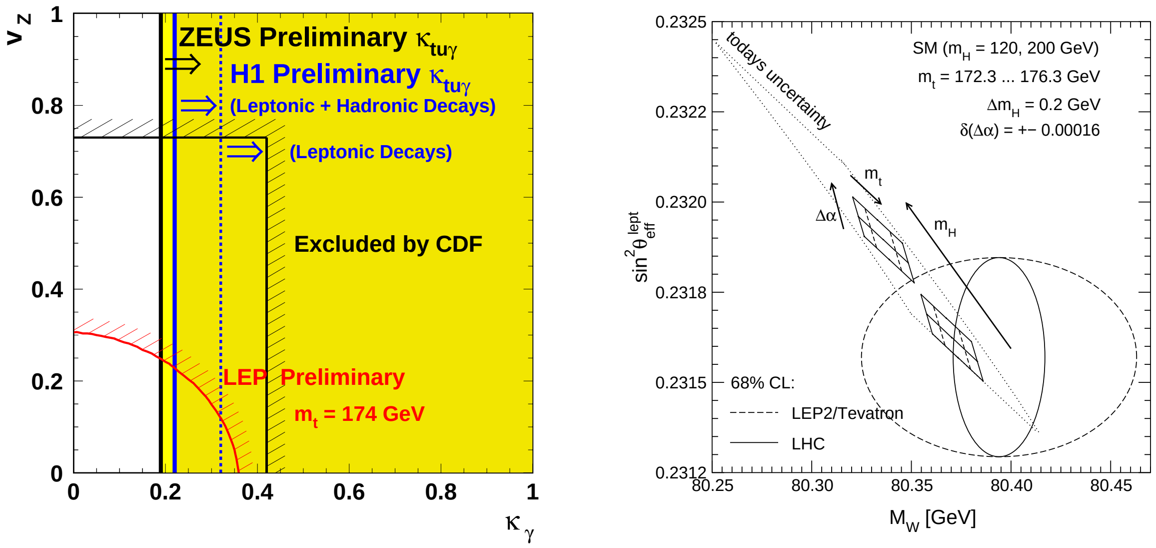

Figure 3: *Left: limits on anomalous FCNC couplings obtained by HERA, LEP II, and CDF. Right: The parametric uncertainties caused by a 2 GeV/*c^2 *(1 GeV/*c^2*, dashed)* M_t *error and by the uncertainty in the hadronic contribution to* $\Delta\alpha$ *in the theoretical prediction to* M_W *and* $\sin^2\theta_{eff}^{lept}$ *are compared to experimental determinations. From Ref. [12].*

3.4 *Using* top quarks

The statistics collected at the Tevatron during Run I allowed D0 and CDF to carry out several additional measurements as well as searches which *use* the top quark as a tag of other processes or as a background. I will briefly mention the most interesting studies in the following.

The top quark samples collected by CDF were used for a direct measurement of $|V_{tb}|$: by fitting the observed yield of events with zero, one, and two SVX b-tags it was possible to determine that $|V_{tb}| = 0.97^{+0.16}_{-0.12}$, or $|V_{tb}| > 0.75$ at 95% CL[22].

Both D0 and CDF[23] searched for $t\bar{t}$ resonances. Models with a dynamically broken EW symmetry (technicolor) predict a top-quark condensate, X, that decays to a $t\bar{t}$ pair. By searching for narrow $t\bar{t}$ resonances, the limit is model-independent. One model[24] predicted a leptophobic $Z' \to t\bar{t}$ with large cross section. The best limit was obtained by the D0 collaboration; for the Z' model, the limit was set at $M_{Z'} > 585$ GeV/c^2 (95% CL).

The studies of the top cross section brought CDF into a deep investigation of their $W+$ heavy flavor data sample. A sample of 13 events with a jet containing both a SVX and SLT b-tag, found to exceed the expectation of 4.4 ± 0.6 events from SM sources, spurred a detailed kinematic analysis. Most of the kinematic characteristics of these events were found to be very different from expectations. A study by some authors claims that the disagreement with a control sample of data with similar biases is at the 10^{-6} level[25]. These anomalies have no explanation in the SM, but are very hard to fit even within exotic models. Run II data will solve this puzzle.

To probe non-standard interactions in the decay of the top quark, spin-spin correlations can be studied: $t\bar{t}$ pairs are not polarized, but their spins should have the same direction in the $t\bar{t}$ rest frame. D0 studied lepton angular correlations in dilepton events, parametrized in terms of k where $\frac{d^2\sigma}{d\cos(\theta_+)d\cos(\theta_-)} = \frac{\sigma(1+k\cos\theta_+\cos\theta_-)}{4}$. The SM predicts $k = 0.88$, and D0 measured $k > -0.2$ at 68% CL[26].

4 The future of top studies

Despite the successes of the conspicuous research program on the top quark carried out at the Tevatron, plus the additional bits from LEP2 and HERA, much more is left to be measured. Fortunately, the Tevatron Run II has already started delivering thousands of $t\bar{t}$ events/year per experiment: these datasets will be used for precision top physics measurements. In a slightly more distant future, the LHC will take over with the huge samples of top quarks it will deliver. But eventually, if a new TeV-scale e^+e^- collider is built, M_t will be determined from threshold scans and our insight in top physics will deepen considerably.

It is impossible to do justice here to the huge amount of work done to anticipate the potential of these experiments in the subject of top physics. I will just highlight some of their most promising aspects in the following.

4.1 The Tevatron upgrade and Run II expectations

The Tevatron collider complex has undergone a massive upgrade during the last five years. The construction of a new main injector with a recycler ring, and the improvements done to the antiproton source and booster ring promise an increase of instantaneous luminosity of an order of magnitude over Run I. The beam energy has also been increased from 900 to 980 GeV, granting up to $30 - 40\%$ increases in the cross section of interesting processes.

Along with the accelerator complex, the CDF and D0 detectors have undergone major improvements. CDF was refurbished with an entirely new tracking system, with seven silicon layers providing precise measurements of track parameters in the region close to the beam line; a revolutionary device provides selection of tracks with significant impact parameter in less than $10\mu s$, enabling triggering capability for hadronic heavy flavor decays. D0 was doted with a $2T$ axial field, and new silicon and fiber trackers; moreover, significant improvements have been made to the calorimeter and muon system.

Run II at the Tevatron promises a great improvement in the measurement of top properties. It is predicted that with 2 fb^{-1} of collected data single top production will be observed and the top mass will be measured with 2 GeV/c^2 accuracy. In order to reach the latter goal, a precise determination of the energy scale of b-quark jets, which was one of the dominant sources of systematics in the run I measurements, will be granted by the availability of a calibration line from $Z \to b\bar{b}$ decays, whose observability has been proven in Run I[27]. Many other precise measurements of top quark properties are in the agenda.

4.2 LHC top physics at a glance

At $\sqrt{s} = 14$ TeV, top quark pairs are produced mainly (90%) through $gg \to t\bar{t}$, with $\sigma_{t\bar{t}} \sim 840$ pb. One year of running at low luminosity ($\sim$ 10 fb^{-1}) will thus allow the collection of 2×10^6 single lepton $t\bar{t}$ events per experiment. These samples grant several precision measurements. M_t determinations are systematics-limited; however, the dominant systematics of different methods are different, so important cross-checks can be made. A precision of $\Delta M_t = 2$ GeV/c^2 can be obtained with only one or two years of running. From the study of single top production ($\sigma_{tX} \sim 300$ pb), $|V_{tb}|$ can be determined to within 10%. Anomalous FCNC couplings can be explored to $10^{-4} \div 10^{-5}$ with 10 fb^{-1}; associated $t\bar{t}H$ production can be observed with 30 fb^{-1} if $M_h = 120$ GeV/c^2, when a precision of 16% in the top Yukawa coupling can be obtained.

Measuring M_t with $1-2$ GeV/c^2 accuracy will considerably tighten the consistency tests of electroweak theory. Fig. 3 shows the level of accuracy that these measurements will reach.

4.3 Top physics at a high energy linear e^+e^- collider

In a high energy e^+e^- collider ($E_{CM} \sim 500$ GeV, 10^{34} $cm^{-2}s^{-1}$, 100 fb^{-1}/year), the total yield of $t\bar{t}$ pairs is expected to reach $\sim 10^5$ $t\bar{t}$ per year of running. The statistical power of these data is smaller than that of LHC, but M_t can be determined with higher accuracy by means of a threshold scan. It is foreseen that the error on M_t could be reduced to $\Delta M_t \sim 100$ MeV/c^2[28]. Moreover, the width of the top quark may be obtained to within a few percent by the shape of the cross section in the threshold region. Another feature is the study of the γtu coupling via the process $e^+e^- \to t\bar{q}$. Studies dealt with the TESLA design ($\sqrt{s} = 500/800$ GeV)[29]: the use of polarized beams could reduce the $Wq\bar{q}'$ background by up to a factor of 8, while increasing $\sigma_{t\bar{q}'}$ by 20%; limits on γtq, Ztq couplings would improve by a factor 2.5, allowing a ×10 improvement over expected LHC limits.

5 Conclusions

The top quark is a very interesting particle: it is the only quark whose mass can be measured directly, and that can be studied free of QCD effects; moreover, the large impact of M_t on radiative corrections makes it worth measuring it with the utmost precision. A handful of $t\bar{t}$ candidates already provided a wealth of new knowledge at the Tevatron Run I. The new Tevatron Run II, LHC, and a new e^+e^- collider are foreseen to do exquisite precision top physics. Top quarks will be used to corner the SM, and hopefully to open an avenue to new physics.

References

[1] C. Berger *et al.*, Phys. Lett. B76, 243 (1978); C. Darden *et al.*, Phys. Lett. B76, 246 (1978).

[2] W. Behrends *et al.*, Phys. Lett. B146, 437 (1983).

[3] H. Albrecht *et al.*, Phys. Lett. B192, 245 (1987).

[4] D. Schaile and P. Zerwas, Phys. Rev. D45, 3262 (1992).

[5] D. Decamp *et al.*, Phys. Lett. B236, 511 (1990).

[6] G. Arnison *et al.*, Phys. Lett. B147, 493 (1984); C. Albayar *et al.*, Z. Phys. C37, 505 (1988).

[7] T. Akesson *et al.*, Z. Phys. C46, 179 (1990).

[8] F. Abe *et al.*, Phys. Rev. Lett. 64, 174 (1990), F. Abe *et al.*, Phys. Rev. D45, 3921 (1992).

[9] F. Abe *et al.*, Phys. Rev. Lett. 73, 225 (1994).

[10] F. Abe *et al.*, Phys. Rev. Lett. 74, 2626 (1995); S. Abachi *et al.*, Phys. Rev. Lett. 74, 2632 (1995).

[11] L. Ibanez and G. Ross, Phys. Lett. B110, 215 (1982).

[12] M. Beneke *et al.*, *Top quark physics*, Hep-ph/0003033.

[13] T. Affolder *et al.*, Phys. Rev. D63, 32003 (2001).

[14] L. Demortier *et al.*, *The top averaging group*, FNAL-TM-2084.

[15] V. Abazov *et al.*, *Ttbar production cross section in ppbar collisions at* $\sqrt{s} = 1.8$ *TeV*, Hep-ex/0205019; T. Affolder *et al.*, Phys. Rev. D64, 032002 (2001).

[16] K. Hagiwara *et al.*, Phys. Rev. D66, 010001 (2002).

[17] D. Acosta *et al.*, Phys. Rev. D65, 91102 (2002); V. Abazov *et al.*, Phys. Lett. B517, 282 (2001).

[18] T. Affolder *et al.*, Phys. Rev. Lett. 84, 216 (2000).

[19] F. Abe *et al.*, Phys. Rev. Lett. 80, 2525 (1998).

[20] R. Barate *et al.*, Phys. Lett. B494, 33 (2000); G. Abbiendi *et al.*, Phys. Lett. B521, 181 (2001).

[21] N. Malden, *Search for single top production in ep collisions at HERA*, submitted to ICHEP 2002; ZEUS collaboration, *Search for events with isolated τ leptons and large missing transverse momentum in ep collisions at HERA*, submitted to ICHEP 2002.

[22] T. Affolder *et al.*, Phys. Rev. Lett. 86, 3233 (2001).

[23] T. Affolder *et al.*, Phys. Rev. Lett. 85, 2062 (2000).

[24] R. Harris, T. Hill, and S. Parke, *Cross section for Topcolor Z' decaying to top-antitop*, Hep-ph/9911288.

[25] D. Acosta *et al.*, Phys. Rev. D65, 52007 (2002); G. Apollinari *et al.*, Phys. Rev. D65, 032004 (2002).

[26] B. Abbott *et al.*, Phys. Rev. Lett. 85, 256 (2000).

[27] T. Dorigo, *Observation of Z decays to b quark pairs at the Tevatron collider*, Hep-ex/9806022.

[28] T. Abe *et al.*, *Linear collider physics resource book for Snowmass 2001 - part 3*, Hep-ex/0106057.

[29] J. Aguilar-Saavedra and T. Riemann, *Probing top flavor-changing neutral couplings at TESLA*, Hep-ph/0102197.