Top Quark Physics

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Since the discovery of the top quark in 1995, extensive studies have examined and paved the ways to measure precisely the properties of the top quark. We discuss the prospects for top quark physics at the Tevatron, LHC, and the Linear Collider.

1 Introduction

The Standard Model in particle physics, with 6 quarks and 6 leptons in the pattern of 3 generations, has been extremely successful in describing all elementary particles and their interactions that have been observed. With the discovery of the b quark in 1977,[1] the discovery of the top quark t in 1995,[2, 3] and the direct observation of the ν_τ neutrino,[4] Fermilab has had a specially important role in the third generation of quarks and leptons. With the Tevatron, the highest energy accelerator in the world since 1985, CDF[2] and D0[3] experiments will have data taking periods Run IIa in 2001 – 2005 and Run IIb in 2006 – 2008 to study the newly discovered Top Quark, CP violation in the B system, and search for Higgs, Supersymmetry, and other new physics. To achieve these goals, Fermilab has completed the construction of the Main Injector new accelerator, while CDF and D0 have significantly upgraded their detectors. The amount of data in Run IIa and IIb is expected to be 20 to 100 times that of Run I in 1991–1996.

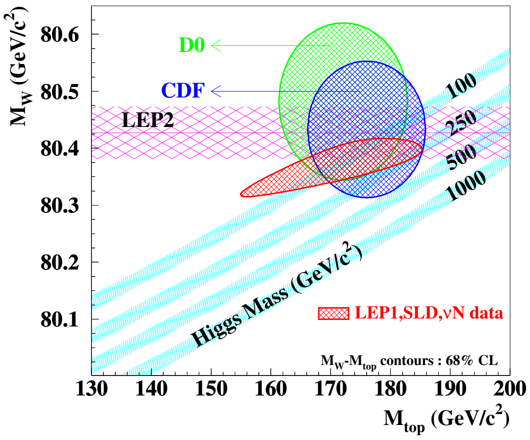
The top quark, due to its heavy mass, can be produced and detected only at Fermilab, until the Large Hadron Collider (LHC) and the e^+e^- Linear Collider. We review some of the results to-date on the top quark, and the extensive studies and great prospects for top quark physics from CDF and D0 at the Tevatron, Atlas and CMS at the LHC, and the Linear Collider.

2 Top Physics at Fermilab Tevatron

The number of events obtained in an experiment can be expressed as: $N_{\rm events} = L\,\sigma\,D$. The luminosity L of protons crossing anti-protons at CDF was 4 pb^{-1} (4 $\times$ 10^{36} /cm^2) in '88–'89, 19 pb^{-1} in '92–'93, and 90 pb^{-1} in '94–'95. Top quarks are produced at the Fermilab Collider predominantly via the process $p\bar{p} \rightarrow t\bar{t} + X$. The $t\bar{t}$ production cross-section for $M_{top} =$ 175 GeV/c^2, even at $\sqrt{\rm s}$ = 1800 GeV, is $\sigma(t\bar{t}) \approx$ 6 pb, which is a factor of $\approx 10^{-10}$ smaller than the $p\bar{p}$ total cross-section. Each top quark is expected to decay into a W boson and a b quark ($t \rightarrow Wb$). Each W decays into either a charged lepton and a neutrino or two quarks. The branching ratio for both W's from a $t\bar{t}$ pair to decay leptonically $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow \ell^+\ell^-\nu\bar{\nu}b\bar{b}$ is: 2/81 for $e\mu$, 2/81 for $ee + \mu\mu$. This simplest "DiLepton" top analysis[5] has a detection efficiency, D, (including branching ratio) of about 1%, resulting in one $t\bar{t}$ event per $\approx 10^{12}$ $p\bar{p}$ collisions, and only a few DiLepton $t\bar{t}$ events in Run I. The "Lepton + Jets" decay modes $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow \ell^{\pm}\nu\ q\bar{q}'\ b\bar{b}$ have larger branching ratios (24/81). To separate from large ($p\bar{p} \rightarrow W + jets$) backgrounds, CDF and D0 use kinematic cuts and/or b-tagging. The SVX-tag identifies displaced vertices measured by silicon vertex detector. The Soft Lepton Tag (SLT) identifies the b quark by its transition $b \rightarrow \ell\nu c$. The SVX-tag has higher efficiency for $t\bar{t}$ and less background than the SLT. The "All Hadronic" multijet decay modes $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow q_1\bar{q}_1{}'\ q_2\bar{q}_2{}'\ b\bar{b}$ also have a large branching fraction (36/81), but the requirements of 6 or more jets and b-tagging are necessary to distinguish the $t\bar{t}$ events from the large QCD multijet backgrounds.

2.1 Run I

From the number of events observed, the detection efficiency and the expected backgrounds, we obtain the cross sections from each channel. The CDF and D0 combined $t\bar{t}$ production cross section was $\sigma(t\bar{t}) = 6.5\ ^{+1.7}_{-1.4}$ pb. The combined CDF and D0 measurements of the top quark mass was $M_{\rm top} = 174.3 \pm 5.1$ GeV/c^2. The figure shows constraints on the mass of the Higgs particle in the $(M_{\rm top}, M_{\rm W})$ plane.



2.1.1 Run II

CDF and D0 have already collected more data during Tevatron Run II than Run I. The production cross-section for $p\bar{p}(q\bar{q}[85\%],\ gg[15\%]) \to t\bar{t}$ at $\sqrt{\rm s}$= 1.96 TeV in Run II is ~35% higher than $\sigma(t\bar{t})$ at $\sqrt{\rm s}$= 1.8 TeV in Run I. Preliminary results on $\sigma(t\bar{t})$ and $M_{\rm top}$ from Run II have been presented at this Conference.[6] Improved precision on top quark mass ($\Delta M_{\rm top} \lesssim 2$ GeV/c^2), branching ratios ($\lesssim$ 10%) and $|V_{tb}|$ can be obtained in Run II. A precision of $\delta\sigma(t\bar{t}) \lesssim 10\%$ will also provide a measurement of $M_{\rm top}$ and a check of QCD prediction for heavy quark production. Observation of new processes $X \to t\bar{t}$ (as in Technicolor,[7] Topcolor,[8] Supersymmetry, and other models) and/or rare decays, for example, $t \to H^+b$, $t \to Zc$ would lead directly to new physics.

In the mass region $120 \leq M_{\rm top} \leq 200$ GeV/c^2, $\sigma(t\bar{t})$ decreases by a factor of 2 as $M_{\rm top}$ increases by 20 GeV/c^2. The uncertainty in cross-section

$\delta\sigma_{t\bar{t}} \approx 5\%$ corresponds to $\Delta M_{\rm top} \approx 1$ GeV/c^2. The theoretical uncertainty is $\delta\sigma_{t\bar{t}}(th) \approx 10\%$. Experimental uncertainty in luminosity has been $\approx 5\%$. The ratios $\dfrac{\sigma_{t\bar{t}}\ (M_{\rm top})}{\sigma_W}$ and $\dfrac{\sigma_{t\bar{t}}\ (M_{\rm top})}{\sigma_{jj}}$ would be independent of uncertainty in luminosity, and may have smaller theoretical & systematic uncertainties than $\sigma_{t\bar{t}}\ (M_{\rm top})$, and may provide a determination of $M_{\rm top}$.

The single top production $p\bar{p} \rightarrow t\bar{b}$ has lower cross section than $t\bar{t}$ but will be accessible. The W-gluon fusion process may provide a measurement of $\Gamma(t \rightarrow Wb)$ and V_{tb}.

The uncertainty in the CDF-D0 combined[9] measurement $M_W = 80.456$ ± 0.059 GeV/c^2 will be improved to ≈ 25 MeV/c^2 in Run IIa. Together with a top mass uncertainty of 2 GeV/c^2, M_H should be constrained (as in the figure) to within 45%.

Higgs boson production processes at Fermilab include: $gg \rightarrow H$ with $\sigma \sim$ 1 pb, the $q\bar{q} \rightarrow WH$ and ZH with lower cross section (but much easier to distinguish from background), and $t\bar{t}H$ production. The Higgs decays mostly into $b\bar{b}$ or WW for M_H below or above M_{WW}. Higgs particle with M_H up to 180 GeV may be observed[10] directly at Fermilab.

Supersymmetry relates particles with different spin, and introduces a new spectrum of particles: a boson for each Standard Model fermion. The Minimal Supersymmetric Standard Model (MSSM), with sparticles $\tilde{q}$, $\tilde{\ell}$, $\tilde{\nu}_\ell$, $\tilde{\chi}^{\pm}$, $\tilde{\chi}^0$, $\tilde{g}$, $\tilde{G}$, and Higgs particles $h, H, A, H^{\pm}$. In the MSSM, the mass of the lightest Higgs boson is predicted to be < 130 GeV/c^2.

3 LHC

Extensive studies have been done for top quark physics for ATLAS and CMS at the LHC[11] with the initial and design luminosities of 10^{33} and $10^{34}/{\rm cm}^2/s$ corresponding to 10 fb^{-1} and 100 fb^{-1} per year. At $\sqrt{\rm s} = 14$ TeV, top quarks are produced predominantly via the $t\bar{t}$ pair production process pp ($q\bar{q}$ [10%], gg [90%]) $\rightarrow t\bar{t}$. With the high cross-section, $\sigma(t\bar{t}) \approx 800$ pb, the production rate is $L\sigma(t\bar{t}) \approx 0.8$ Hz, and 8 million $t\bar{t}$ produced per year with the initial luminosity, resulting in 100k DiLepton events and 600k

Lepton + jets events with b-tag.

For top mass measurement from Lepton + jets events, the dominant systematic uncertainties are due to jet energy scale and final state radiation. For the DiLepton events, $< M_{\ell b} >$, $M_{\ell,slt}$, and full kinematic reconstruction Likelihood methods (similar to those in CDF and D0) have been studied. Top mass resolution of 2 to 1 GeV/c^2 will be achieved.

The $t\bar{t}$ pair production cross-section will be an important measurement at the LHC. The uncertainty on luminosity is $\Delta L/L \approx 5$ - 10%. Possible $t\bar{t}$ resonances could increase the observed $\sigma(t\bar{t})$. Non-Standard Model decay modes, e.g. $t \to H^+ b$, would result in lower observed $\sigma(t\bar{t})$.

3.1 Top Quark Decays

The top quark is expected to decay into Wb (99.9%), Ws (0.1%), Wd (0.01%) in the Standard Model. In $t\bar{t}$ events, the ratio of the number of events with two b quarks to the number of events with one b (or $\bar{b}$) quark, $R_{2b/b} = BR(t \to Wb)/BR(t \to Wq) = (|V_{tb}|^2/(|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2) = |V_{tb}|^2$, provides a measurement of V_{tb}. At the LHC, the ratio can be determined to a statistical uncertainty of $\delta R_{\frac{2b}{b}} \approx 0.2\%$ (stat) for 10 fb^{-1}.

The top quark is expected to decay weakly $BR(t \to WX) \approx 100\%$. In $t\bar{t}$ events, the ratio of the number of events with two high P_T leptons to the number of events with one lepton, $R_{\frac{\ell\ell}{\ell}} = BR(W \to \ell\nu) = 2/9$. Additional decay modes, for example, $t \to H^+ b$ followed by $H^+ \to \tau\nu, cs$, would reduce the experimentally observed ratio. At LHC, this ratio can be determined to a statistical uncertainty of $\delta R_{\frac{\ell\bar{\ell}}{\ell}} \approx 0.5\%$ (stat) for 10 fb^{-1}.

3.2 Top Quark Rare Decays

The possible decay mode $t \to WbZ$ with a branching ratio of about 10^{-7} may provide a sensitive probe of M_{top}. The branching ratio $BR\ (WbZ)$ varies by a factor of 3 in $\Delta M_{\mathrm{top}} \approx 5$ GeV/c^2, however, the experimental sensitivity for this decay is 10^{-3} with 10 fb^{-1} of data.

Flavor changing neutral current (FCNC) decay modes have small branching ratios in the Standard Model, $t \to Zu, Zc$ (10^{-12}), $t \to \gamma u, \gamma c$ (10^{-12}), $t \to gu, gc$ (10^{-10}). In MSSM, these decay rates are 10^4 times higher. It will be important also to search for $t \to H^+b$ and the decay modes $b^{'} \to Wt \to WWb$ and $t \to Wb^{'} \to WWc$ involving the possible fourth generation of quarks.

3.3 Single Top Quark production

The Wg, Wt, and W^* single top quark production processes ($pp \to tX \to WX$) with 250, 60, and 10 pb cross-sections can be observed at the LHC. These processes provide a direct measurement of $\Gamma(t \to Wb)$ and measurements of V_{tb} to accuracies of 0.4%, 1.4%, and 2.7% for 30 fb^{-1}. In these t production processes, both the t and W are polarized and provide a test of the $V - A$ structure of the charged current weak interaction of the top quark.

3.4 $X \to t\bar{t}$

The $M_{t\bar{t}}$ distribution may provide evidence for new particle X decaying into $t\bar{t}$. The decay mode $H \to t\bar{t}$ (for $M_H > 2M_{\mathrm{top}}$) would be difficult to observe, because $\Gamma(H) = 63$ GeV and $BR\ (t\bar{t}) = 17$ % for $M_H = 500$ GeV. In MSSM, for $m_A,\ m_H > 2M_{\mathrm{top}}$, $BR\ (H, A \to t\bar{t}) \approx 100\%$ for $tan\ \beta = 1$.

3.5 Top Quark Yukawa Coupling

In the Standard Model, the Yukawa coupling $y_f = \sqrt{2}\frac{m_f}{v}$ is proportional to the mass of the fermion. The top quark, with its large mass and $y_t \approx 1$, is specially important for testing the coupling between ferminons and the Higgs boson. The top quark Yukawa coupling can be directly measured in the process $pp \to t\bar{t}H$. For $M_{\mathrm{H}} \sim 120\ \mathrm{GeV/c^2}$, from the decay mode $t\bar{t}H \to \ell\nu j_1 j_2 b\bar{b}b\bar{b}$, the top quark Yukawa coupling can be determined to a statistical uncertainty $\Delta y_t / y_t$ (stat) of 16% for 30 fb^{-1} of data.

4 Linear Collider

The Linear Collider[12, 13, 14] will be able to directly observe and/or set stringent limits on new physics, and provide precision measurements of the properties of the top quark and other important parameters including α_s, M_W, and M_H. The $t\bar{t}$ production cross-section is $\sigma(e^+e^- \to t\bar{t}) \approx 700$ fb for $E_{cm} \approx 2m_{\rm top}$, would produce $\approx 70,000$ $t\bar{t}$ events with 100 fb^{-1}. The largest background is $\sigma(e^+e^- \to WW) \approx 5$ pb.

4.1 $t\bar{t}$ Threshold Scan

Physics at the $e^+e^- \to t\bar{t}$ production threshold has been studied in detail, including uncertainties in beam energy, beamstrahlung, backgrounds, and detector resolutions. Theoretical uncertainties include top mass definitions (M^{Pole}, M^{1S}, M^{PS}, $M^{\overline{MS}}$), Next-to-Next Leading Order corrections, and the effects of the uncertainties in important parameters including $\Delta\alpha_s$, $\Delta\Gamma_t$, and ΔM_H. A precision for the top mass measurement of $\Delta M_{\rm top} \leq 100$ MeV/c^2 may be achieved at $t\bar{t}$ threshold with 10 fb^{-1}. The top width Γ_t $= G_F M_t^3/\sqrt{2}8\pi \approx 1.5$ GeV may be obtained from t momentum distribution and/or forward–backward asymmetry, with a resolution of $\delta\Gamma_t \approx 3$–6 % with 200 fb^{-1}.

4.2 $M_{\rm top}$ from $t\bar{t}$ DiLepton events

The top quark mass can also be determined from direct reconstruction of $e^+e^- \to t\bar{t} \to W^+bW^-\bar{b} \to \ell^+\ell^-\nu\bar{\nu}b\bar{b}$ DiLepton events. In contrast to the threshold scan, the precision of $M_{\rm top}$ from direct reconstruction is independent of uncertainties in luminosity and cross-section. At $\sqrt{\rm s}$ beyond the $t\bar{t}$ threshold, $M_{\rm top}$ can be measured in addition to Higgs, Supersymmetry, and other new physics. CDF and D0 obtained $M_{\rm top} = 174.3 \pm 5.1$ GeV/c^2 from direct reconstruction of $t\bar{t}$ events. The top quark mass will be determined to a precision of 1 to 2 GeV/c^2 at the Tevatron and the LHC. For direct reconstruction, the DiLepton channel has the smallest systematic uncertainty, in comparison with the Lepton + Jets and Multi-jet channels. In contrast to the hadron colliders, the beam energy at the Linear Collider provides constraints in the kinematic reconstruction. A precision[15] of $\Delta M_{\mathrm{top}} \leq 200$ MeV/c^2 on the top quark mass can be achieved at the Linear Collider.

4.3 $e^+e^- \to t\bar{t}H$

From decay modes $t\bar{t}$ H $\to$ 8 jets or Lepton + 6 jets, the top quark Yukawa coupling can be determined. For $M_{\mathrm{H}} \sim 120$ GeV/c^2, a statistical uncertainty δy_t (stat) of 14% can be obtained with 100 fb^{-1} at $\sqrt{\mathrm{s}} = 700$ GeV.

4.4 $t\bar{t}$ Spin correlations

In the decay $t \to Wb \to \ell\nu b$, the lepton angular distribution provides a measurement of the polarization of the top quark. The $e^+e^- \to \gamma, Z \to t\bar{t}$ process, especially with polarized beams, is ideal to study the t polarization, and electroweak and anomalous (including CP violating) couplings.

5 Summary

The discovery of the top quark opened a new window to new physics. Top Quark physics is just beginning. CDF and D0 have already collected more data during Tevatron Run II than Run I. Lots of top quark and other physics will be available, (and there will be new searches for Higgs, SUSY and other new physics) in the next 2–5 years with 10–100 times more data at Fermilab. At the LHC, Atlas and CMS will have $\sim$ 1000 times more $t\bar{t}$ events than at the Tevatron. The sensitivity to t rare decays will be best at LHC.[11, 16]

The Linear Collider will provide precise measurements of the properties of the top quark. The top mass can be determined to a precision of $\Delta M_{\mathrm{top}} < 200$ MeV/c^2 with $t\bar{t}$ threshold scan, or direct reconstruction from the DiLepton events, or the GigaZ.[17] Top quark width Γ_t, couplings, polarization, and Yukawa coupling Y_{tH} can be determined with good precision. Evidence for new particles decaying into top quark pairs $X \to t\bar{t}$ would be a signature for new physics. The top quark is a key to the electroweak symmetry breaking and the understanding of Flavor.

	Tevatron	LHC	LC	
Beams	$p\overline{p}$	pp	e^+e^-	
Luminosity	10^{32-33}	10^{33-34}	1–5 $\times$ 10^{34}	$/\mathrm{cm}^2/s$
$t\,\bar{t}$ Cross Section	7	800	0.7	pb
Detection Efficiency	~ 0.1	~ 0.1	$\gtrsim 0.6$	
$\Delta(M_{\mathrm{top}})$	1–2	1–2	0.1–0.2	GeV/c^2
$\delta\Gamma_t$			$< 10\%$	
δV_{tb}	6%	5%	$< 5\%$	
Y_{tH} $(t\bar{t}H)$		$\leq 16\%$	$\leq 10\%$	
Anomalous δd_{tg}		10^{-3}	10^{-1}	
$\delta d_{t\gamma}$, δd_{tZ} couplings			10^{-2}	

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References

[1] S. W. Herb, *et al.*, Phy. Rev. Lett. **39**, 252 (1977).

[2] CDF Collaboration, (www-cdf.fnal.gov/physics/physics.html)
F. Abe, *et al.*, PRD **50**, 2966 (1994); PRL **74**, 2626 (1995).

[3] D0 Collaboration, (www-d0.fnal.gov/public/d0_physics_v2.html)
S. Abachi, *et al.*, PRL **72**, 2138 (1994); **74**, 2422 (1995); **74**, 2632 (1995).

[4] DONUT Experiment, www-donut.fnal.gov

[5] G. P. Yeh, Symposium. on 4th Family of Quarks and Leptons, New York Academy of Sciences, Santa Monica, Feb. 1989.

[6] Azzi, P., for CDF and D0 Collaborations,
http://conferences.fnal.gov/lp2003/program/index.html#S1
Lepton Photon 2003, Fermilab; Gerdes, D., this ICFP Conference.

[7] E. Eichten, K. Lane, Phys. Lett. B **327**, 129 (1994).

[8] C. T. Hill and S. J. Parke, Phys. Rev. D **49**, 4454 (1994).

[9] Tevatron Electroweak Working Group, tevewwg.fnal.gov/wz/
LEP Electroweak Working Group, www.cern.ch/LEPEWWG/

[10] www-d0.fnal.gov/Run2Physics/public/higgs/HSS_D0_CDF.pdf

[11] M. Beneke, et al, Top Quark Physics, Report of the 1999 Workshop on Standard Model Physics (and more) at LHC, arXiv:hep-ph/0003033.

[12] Tesla TDR, J. A. Aguilar–Saavedra, et al, March 2001, hep-ph/0106315, tesla.desy.de/new_pages/TDR_CD/PartIII/physic.html

[13] American Linear Collider Working Group, "Linear Collider Physics Resource Book for Snowmass 2001" Fermilab-Pub-01/058-E, SLAC-R-570. www.slac.stanford.edu/grp/th/LCBook/

[14] K. Abe et al., ACFA Linear Collider Working Group,
arXiv:hep-ph/0109166; http://lcdev.kek.jp/RMdraft/

[15] J. Antoš and G. P. Yeh, LCWS99, Sitges, Barcelona, Spain (1999); Fermilab-Conf-99/260

[16] http://conferences.fnal.gov/hadroncollider/

[17] J. Erler, et al, Physics Impact of GigaZ, arXiv:hep-ph/0005024.