Fermi National Accelerator Laboratory

FERMILAB-Conf-99/143-E
D0 and CDF

Studies of the Top Quark at the Tevatron

Dhiman Chakraborty
For the D0 and CDF Collaborations

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

May 1999

Published Proceedings of the *13th Topical Conference on Hadron Collider Physics*, Mumbai, India, January 14-20, 1999

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

STUDIES OF THE TOP QUARK AT THE TEVATRON

DHIMAN CHAKRABORTY
Department of Physics and Astronomy
State University of New York at Stony Brook
Stony Brook, NY 11794, USA
E-mail: dhiman@fnal.gov
(For DØ and CDF Collaborations)

We report on studies of the top quark, beyond the measurements of its mass and production cross section, which have been carried out recently by the CDF and DØ collaborations, based on $\sim 110 \pm 6$ pb^{-1} of proton-antiproton collisions at a center-of-mass energy of 1.8 TeV. Each experiment has searched for $t \to H^+ b$ decays and, from the lack of observable signal, excluded previously unexplored regions of the [M_{H^+},$\tan\beta$] parameter space. DØ has studied the correlation between the spin states of pair-produced top quarks, and CDF has studied the helicity of the W bosons produced in the decay of top quarks. Within large statistical uncertainties, both measurements agree with predictions of the standard model.

1 Introduction

Since the discovery of the top quark by CDF and DØ at Fermilab in 1995, both experiments have continued studying it. Run 1 (1992-96) of the Tevatron accelerator provided each experiment with $\sim 110 \pm 6$ pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. This data has been used not only to measure the mass of the top quark (m_t) and its pair-production cross section ($\sigma(t\bar{t})$), but also to study other aspects of its production and decay. The large mass of the top quark makes it an ideal testing ground for strong and electroweak couplings at a large mass scale, of interest for studies of mass-dependent couplings, and a good place to look for production of particles beyond the standard model (SM), most of which are believed to be heavier than all other fermions observed so far. Studies of three such topics have been completed recently, and are presented in the following sections.

The CDF and DØ detectors are described elsewhere [1]. The reconstruction algorithms for jets, muons, electrons, and neutrinos employed in the analyses presented here are the same as those used in the previous top quark analyses, and the same event selection criteria are used as in the measurements of $\sigma(t\bar{t})$ [2] and m_t [3]. The SM requires a t quark to decay almost exclusively to a W boson and a b quark, i.e., $B(t \to W^+ b) \approx 1$. The selection criteria are summarized in Table 1, where "dilepton" cuts are optimized to select $t\bar{t}$ events when each W decays to $e\nu$ or to $\mu\nu$, and "single lepton" cuts are optimized for cases when one W decays to $e\nu$ or to $\mu\nu$ while the other decays to $q\bar{q}'$.

2 Search for a charged Higgs boson lighter than the top quark

2.1 Motivation and overview

The Higgs sector of the SM consists of a single complex doublet scalar field responsible for breaking electroweak symmetry and generating gauge boson masses. The

Table 1. Summary of $t\bar{t}$ event selection criteria used by DØ and CDF in dilepton and single-lepton channels, signal acceptance (assuming $m_t = 175$ GeV), expected background, and the number of events observed in data. For DØ single-lepton analysis, the numbers in square brackets correspond to events that contain at least one jet tagged as a b-jet candidate by an associated (non-isolated) muon. Subtle variations between subchannels and further details are described in the references.

	DØ		CDF	
	single lepton	dilepton	single lepton (SVX)	dilepton
$p_T(l)$	>20 GeV	>20 GeV	>20 GeV	>20 GeV
$\lvert\eta_{e(\mu)}\rvert$	<2.0 (1.7)	<2.0 (1.7)	<1.0	<1.0
$\not{E}_T$	>25 [20] GeV	>20 GeV	>20 GeV	>25 GeV
$E_T(j)$	>15 [20] GeV	>20 GeV	>15 GeV	>10 GeV
$\lvert\eta_j\rvert$	<2.0	<2.5	<2.0	<2.0
# of jets (n_j)	≥ 4 [3]	≥ 2	≥ 3	≥ 2
# of b tags	0 [≥ 1]	–	≥ 1 (SVX)	–
Aplanarity	>0.065 [0.040]	–	–	–
$H_T \equiv \sum_{i=1}^{n_j} E_T(j_i)$	>180 [110] GeV	>120 GeV	–	–
Signal acceptance (%)	3.40 ± 0.55	0.65 ± 0.10	3.7 ± 0.5	0.74 ± 0.08
Estimated background	11.2 ± 2.0	1.5 ± 0.3	10.6 ± 1.6	2.5 ± 0.4
Events observed ($n_{\rm obs}$)	30	6	34	9

simplest extension of the Higgs sector to two complex doublets appears in many theories beyond the SM, including supersymmetry (SUSY). Our studies are based on the two-Higgs-doublet model where one doublet couples to up-type quarks and neutrinos, and the other couples to down-type quarks and charged leptons, as required by SUSY [4]. Under these circumstances, electroweak symmetry breaking leads to five physical Higgs bosons: two neutral scalars h^0 and H^0, a neutral pseudoscalar A^0, and a pair of charged scalars $H^\pm$. The extended Higgs sector has two new parameters: M_{H^+} and $\tan\beta$, where $\tan\beta$ is defined as the ratio of the vacuum expectation values of the two Higgs fields.

Direct searches for $e^+e^- \to H^+H^-X$ at LEP have set lower limits of 57.5–59.5 GeV on M_{H^+} at the 95% confidence level (CL) irrespective of $\tan\beta$ [5]. A measurement of the inclusive $b \to s\gamma$ decay rate gives CLEO an indirect limit of $M_{H^+} > [(244 + 63/(\tan\beta)^{1.3}]$ GeV, assuming only a two-Higgs-doublet extension to the SM [6]. From a measurement of the $b \to \tau\nu X$ branching fraction, ALEPH constrains $\tan\beta/M_{H^+} < 0.52$ GeV^{-1} at 90% CL [7].

At leading order, the H^+ coupling to a down-type (up-type) quark or neutral (charged) lepton is proportional to the fermion mass multiplied by $\tan\beta$ ($\cot\beta$). If $H^\pm$ exist with $M_{H^+} < m_t - m_b$, and $\tan\beta$ is either very large or very small, then $B(t \to H^+b)$ can be significant. We assume that $B(t \to H^+b) + B(t \to W^+b) = 1$. For any given $\tan\beta$, $B(t \to H^+b)$ decreases as M_{H^+} increases. It is further assumed that M_{S^0} ($S^0 = h^0$, H^0, or A^0) are large enough for the decays $H^+ \to S^0W^+$ to be highly suppressed for real or virtual S^0 and W^+ bosons. Decays $H^+ \to V^0W^+$, where $V^0 = \gamma$ or Z, are absent at the tree level [8]. Hence, H^+ can only decay to fermion-antifermion pairs. Consequently, one might expect $H^+ \to \tau^+\nu$ (favored if $\tan\beta$ is large) and $H^+ \to c\bar{s}$ (favored if $\tan\beta$ is small) to be the only significant possibilities. Indeed, $B(H^+ \to \tau^+\nu) \approx 1$ if $\tan\beta > 10$. But if $\tan\beta < 2$ and $M_{H^+} > 130$ GeV, then the large mass of the t quark causes $B(H^+ \to t^*\bar{b} \to W^+b\bar{b})$ to exceed $B(H^+ \to c\bar{s})$ [9].

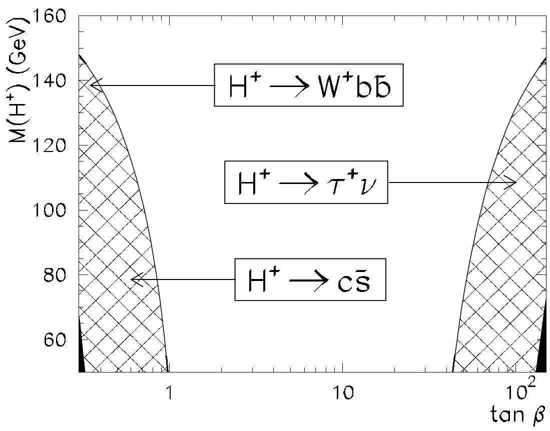

Figure 1. The parameter space explored in the searches for $t \to H^+b$. Regions where $B(t \to H^+b) > 0.5$ are shown cross-hatched, with labels for various decay modes of the charged Higgs indicating their regions of dominance. Regions where $B(t \to H^+b) > 0.9$ (dark shaded areas) are not considered.

Figure 1 shows the region of the $[M_{H^+}, \tan\beta]$ plane examined in the DØ analysis [10]. The lower and upper boundaries on $\tan\beta$ (0.3, 150) are required for the applicability of perturbative calculations in H^+ Yukawa coupling to t and b quarks. Also shown in Fig. 1 are the decay modes of H^+ that dominate in different parts of the parameter space. Analogous charge-conjugate expressions hold for H^-.

2.2 Analysis methods

A strong dependence of signal characteristics on the parameters of the model makes a direct ("appearance") search for signal a difficult task. Both DØ and CDF therefore perform an indirect ("disappearance") search using selection criteria optimized for the SM channel $t\bar{t} \to W^+bW^-\bar{b}$. The disappearance search by CDF uses both dilepton and single-lepton final states, while that by DØ uses only the latter. The single-lepton events used by CDF in this analysis are required to have at least one of the jets tagged as a b-jet candidate by a secondary decay vertex (SVX) separated from the reconstructed primary (collision) vertex. One expects the efficiencies of these criteria for channels involving $t \to H^+b$ decays to be substantially smaller than that for the SM channel. This is indeed true if the dominant decay mode for H^+ is either $\tau^+\nu$ or $c\bar{s}$. Consequently, if the assumption of $B(t \to W^+b) = 1$ leads to a measurement of the top quark pair production cross section $\sigma(t\bar{t})$ in good agreement with theoretical predictions, then those regions of the $[M_{H^+}, \tan\beta]$ parameter space where $B(t \to H^+b)$ is sufficiently large can be excluded except where $B(H^+ \to W^+b\bar{b})$ is large. CDF has also carried out an appearance search for $t \to H^+b$, with $H^+ \to \tau^+\nu$, using hadronic decay modes of τ. The reconstruction algorithm for τ leptons and the event selection criteria for this search, effective only if $\tan\beta > 1$, can be found elsewhere [11].

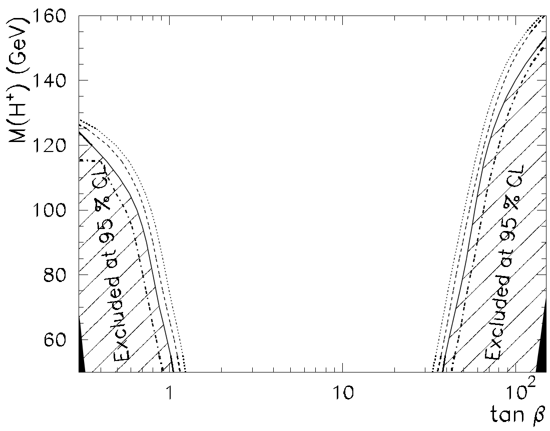

Figure 2. The DØ 95% CL exclusion boundaries in the [M_{H^+},$\tan\beta$] plane for $m_t = 175$ GeV, and value of $\sigma(t\bar{t})$ set to 5.5 pb (hatched area, solid lines), 5.0 pb (dashed lines), and 4.5 pb (dotted lines). The thicker dot-dashed lines inside the hatched area represent the exclusion boundaries obtained from a frequentist analysis for $\sigma(t\bar{t}) = 5.5$ pb.

The measured values of $\sigma(t\bar{t})$ and m_t are based on the assumption of $B(t \to W^+b) = 1$, and cannot be used in a search for $t \to H^+b$. Hence, $\sigma(t\bar{t})$ and m_t are treated as input parameters. From the ratio of numbers of events observed in single-lepton and dilepton channels, CDF also derives a limit which is independent of $\sigma(t\bar{t})$.

2.3 Results

DØ performs a Bayesian analysis of data, assuming the prior probability density to be uniform in M_{H^+} and in $\log_{10}(\tan\beta)$. The results, corresponding to $m_t = 175$ GeV, are shown in Fig. 2 for three values of $\sigma(t\bar{t})$. Figure 2 also shows the result of a frequentist analysis of DØ data wherein a point in the parameter space is excluded if more than 95% of Monte Carlo simulations of DØ Run 1 at that point yield $n_{\rm obs} < 30$ (see Table 1). CDF only performs a frequentist analysis, the results of which are shown in Fig. 3 for two values of $\sigma(t\bar{t})$. Due caution must be exercised in comparing Bayesian and frequentist results since there is a difference between the two approaches in the interpretation of "confidence level". For a given value of $\sigma(t\bar{t})$, within the range 170 GeV $< m_t <$ 180 GeV, the excluded region increases with increasing m_t by an extent comparable to that from a similar fractional decrease in $\sigma(t\bar{t})$ at a fixed m_t.

A comparison between Figs. 1, 2 and 3 shows that, for $\sigma(t\bar{t}) = 5.0$ pb and m_t= 175 GeV, all regions of the [M_{H^+},$\tan\beta$] parameter space where $B(t \to H^+b) >$ 0.32 (0.41), except where $B(H^+ \to W^+b\bar{b})$ is large, are excluded by CDF (DØ) at the 95% CL.

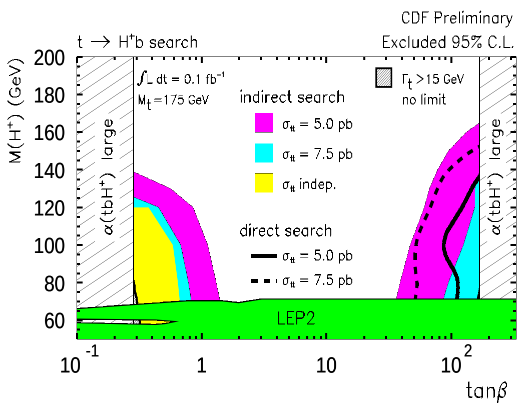

Figure 3. The CDF 95% CL exclusion boundaries in the $[M_{H^+}, \tan\beta]$ plane for $m_t = 175$ GeV, and value of $\sigma(t\bar{t})$ set to 7.5 pb (light and medium shaded areas) and 5.0 pb (all shaded areas). The thicker lines inside the shaded areas represent the exclusion boundaries obtained from the $H^+ \to \tau^+\nu$ appearance analysis: $\sigma(t\bar{t})$= 5.0 pb (solid line) and $\sigma(t\bar{t})$= 7.5 pb (dashed line). The light shaded area on the lower left side is excluded by the $\sigma(t\bar{t})$-independent ratio method. The shaded band at the bottom is excluded by the LEP experiments at the 95% CL.

3 Spin correlation in $t\bar{t}$ production

3.1 Motivation and overview

Because of its large mass, the top quark lifetime (τ_t) is smaller than the timescale for its hadronization which subsequently induces spin decorrelation. Thus, the decay products of top quarks produced in a definite spin state should display angular correlations that characterize the production process. Observation of a departure from the expected spin correlation could be indicative of physics beyond the SM, such as the observed state being something other than the $SU(2)$ partner of the bottom quark, or the presence of non-standard interactions in the decay of the top quark. Also, the study of spin correlations allows us to examine properties of a bare quark, free from the long-distance effects of QCD, such as hadronization and confinement. No other quark observed so far has a lifetime short enough to offer this opportunity.

To leading order in electroweak coupling, the relative rates for decay products in the rest frame of the top quark can be written as

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_i)} = \frac{1+\alpha_i\cos\theta_i}{2} \tag{1}$$

where Γ is the decay width, and θ_i is the angle between the direction of spin quantization and the direction of flight of the particle represented by i [12]. For $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, $q\bar{q'}$ annihilation through the s-channel via a spin-1 gluon is expected to account for $\sim 90\%$ of the cross section for top pair production. The values of the correlation coefficient α for various decay products of the top quark in $q\bar{q'} \to g^* \to t\bar{t}$ events are: e, μ, τ, d, s : $1; \nu_e, \nu_\mu, \nu_\tau, u, c$: -0.31; and b : -0.41.

Angular distributions of down-type quarks and charged leptons are therefore the most sensitive to the spin characteristics of the top quark.

The optimal basis for quantizing the spin of a top quark, pair-produced in a $q\bar{q}$ collision, is given by an angle ψ in the constituent rest frame,

$$\tan\psi = \frac{\beta^2 \sin\lambda\cos\lambda}{1-\beta^2\sin^2\lambda} \tag{2}$$

where λ is the angle between the 3-momentum of the top quark (antiquark)and that of the incident quark (antiquark), and β is the velocity ($c = 1$) of the top quark [13]. If the angle between a negatively (positively) charged lepton or d ($\bar{d}$) -type quark and the spin quantization axis is denoted by θ_- (θ_+), then the differential decay rate of the top quark can be parametrized as

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_+\cos\theta_-)} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4} \tag{3}$$

All information on spin correlation is contained in the parameter κ.

3.2 Analysis and results from DØ

In view of the difficulty in separating jets originated by down-type quarks from those originated by up-type quarks or gluons, and due to difficulties in τ identification, this analysis is restricted to dilepton channels (both Ws decaying leptonically) ee, $\mu\mu$ and $e\mu$. The selection criteria, summarized in Table 1, and the event fitting procedure, are identical to those described in Ref. [3]. The analysis relies on probability density estimator (PDE) [14], a multivariate events classifier, to estimate the likelihood of an event arising from signal or from background. The probability density, shown as a function of κ in the bottom right panel of Fig. 4, suggests that DØ data favors a positive value for κ. This is consistent with the SM expectation of $\kappa \approx 0.9$, although the limited statistics from Run 1 prevent us from making a definitive statement. Simulations of Run 2 data based on the SM, assuming a data sample consisting of 150 events, indicate that negative values of κ can be ruled out at a confidence level corresponding to more than 2.5σ.

4 Polarization of W in top quark decay

4.1 Motivation and overview

In the SM, a majority of top decays produce a W with zero helicity ($h_W = 0$) in the top rest frame. At tree level, the fraction of these "longitudinal Ws" is given by

$$\mathcal{F}_0 \equiv \frac{\Gamma(h_W=0)}{\Gamma(h_W=-1)+\Gamma(h_W=0)} = \frac{m_t^2/(2m_W^2)}{1+m_t^2/(2m_W^2)} \tag{4}$$

Assuming $m_t = 175$ GeV, $\mathcal{F}_0 \approx 0.70$. A measurement of $\mathcal{F}_0$ can be used as a powerful probe for non-standard t-W-b couplings. Alternatively, in the language of electroweak symmetry breaking, one can say that the longitudinal mode of the W couples to fermion mass, that the massive top quark is therefore exposing this mode, and that this could be a good place to look for surprises.

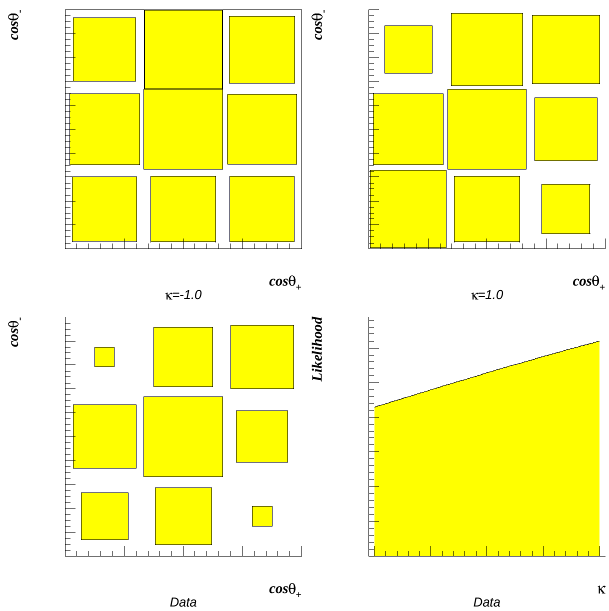

Figure 4. Result of analysis of $t\bar{t}$ spin correlation by DØ. The two top panels show the distributions of $\cos\theta_-$ vs $\cos\theta_+$ expected for $\kappa = -1$ and $\kappa = 1$, respectively, including the estimated contribution from background. The bottom left panel shows the distribution observed in data. The bottom right panel shows the result of a 2-dimensional binned likelihood fit to data, as a function of κ.

4.2 Analysis and results from CDF

CDF has performed a measurement of $\mathcal{F}_0$ using the dilepton and single-lepton subsets of the Run 1 top candidate sample used for their mass analysis. For this analysis, a single-lepton event is not required to have a jet tagged as a b-jet candidate. The selection criteria are otherwise similar to those given in Table 1. The total number of leptons available for the analysis is 105, with an estimated background of 39.1 ± 6.7.

The basic idea is that the charged lepton from a left-handed W (W_-) tends to move opposite to the direction of flight of the W, while that from a longitudinal W (W_0) tends to move perpendicular to it in the top rest frame. Transforming to the laboratory frame, on average, charged leptons from W_0 are expected to have larger transverse momenta than those from W_-. Instead of exploiting the angular correlations between partons, this method uses only the most accurately measured quantities, namely momenta of charged leptons, and is free from large combinatorial backgrounds. The analysis relies on templates of lepton p_T distributions for W_0, W_-, and background modeled by Monte Carlo. An unbinned maximum log-likelihood fit is used to extract the fraction $\mathcal{F}_0$ of top quarks that decay to W_0. The result of this fit is, as shown in Fig. 5, $\mathcal{F}_0 = 0.97 \pm 0.37(\text{stat}) \pm 0.11(\text{sys})$ if the right-handed component $\mathcal{F}_+$ is assumed to be zero.

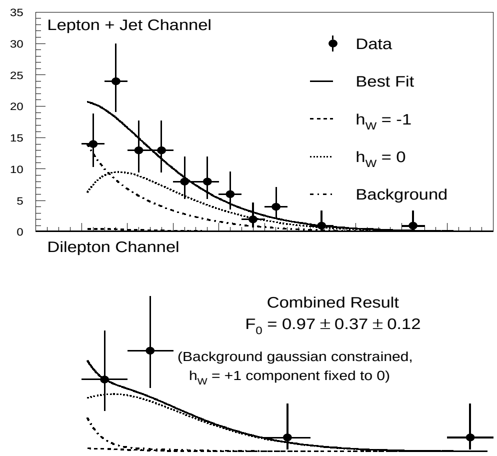

Figure 5. Fit for fraction of W_0 in top quark decay using transverse momenta of charged leptons.

5 Summary and conclusions

We have presented four recently completed analyses, namely, two searches for charged Higgs Bosons in decays of top quarks, a study of top-antitop spin correlations, and a measurement of W helicity in top decays. Neither DØ nor CDF finds any evidence for $t \to H^+b$, consequently ruling out a large part of previously unexplored regions of $[M_{H^+}, \tan\beta]$ parameter space. Measurements of $t\bar{t}$ spin correlation and the fraction of longitudinally polarized W bosons in top decays are consistent with the SM within large statistical uncertainties. As a result of accelerator and detector upgrades, we expect from Run 2 a 30 times larger $t\bar{t}$ yield and a much higher $S : B$ ratio. This improvement will greatly benefit all of the above analyses.

Acknowledgments

We are grateful to D. P. Roy, J. Wudka, S. Mrenna, and S. Parke for valuable discussions on theoretical aspects of the analyses, and for help with Monte Carlo simulations. We thank the Fermilab and collaborating institution staffs for contributions and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à L'Energie Atomique (France), Ministry for Science and Technology and Ministry for Atomic Energy (Russia), CAPES and CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), CONICET and UBACyT (Argentina), Instituto Nazionale di Fisica Nucleare (Italy), Ministry of Science, Culture, and Education (Japan), National Sciences and Engineering Research Council (Canada), and the A. P. Sloan Foundation.

References

1. CDF Collaboration, F. Abe *et al.*, Nucl. Instrum. Methods A **271**, 387 (1988); DØ Collaboration, S. Abachi *et al.*, Nucl. Instrum. Methods A **338**, 185 (1994).
2. DØ Collaboration , B. Abbott *et al.*, Phys. Rev. Lett. **79**, 1203 (1997); CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **80**, 2773 (1998); CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **80**, 2779 (1998).
3. DØ Collaboration, B. Abbott *et al.*, Phys. Rev. Lett. **79**, 1197 (1997); DØ Collaboration, B. Abbott *et al.*, Phys. Rev. Lett. **80**, 2063 (1998); CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **80**, 2767 (1998); CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **82**, 271 (1999).
4. J. F. Gunion, H. E. Haber, G. Kane, and S. Dawson, "The Higgs Hunter's Guide", Addison-Wesley (1990).
5. ALEPH Collaboration, CERN-EP/99-011 submitted to Phys. Lett. B; L3 Collaboration, CERN-EP/98-149 submitted to Phys. Lett. B; OPAL Collaboration, CERN-EP/98-173 submitted to Eur. Phys. J. C, hep-ex/9811025.
6. CLEO Collaboration, M. S. Alam *et al.*, Phys. Rev. Lett. **74**, 2885 (1995).
7. ALEPH Collaboration, D. Buskulic *et al.*, Phys. Lett. B **343**, 444 (1995).
8. J. Rosiek, Phys. Rev. D **41**, 3464 (1990).
9. E. Ma, D. P. Roy, and J. Wudka, Phys. Rev. Lett. **80**, 1162 (1998).
10. DØ Collaboration, B. Abbott *et al.*, FERMILAB PUB-99/029-E, submitted to Phys. Rev. Lett., hep-ex/9902028.
11. CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 357 (1997).
12. G. Mahlon and S. Parke, Phys. Lett. **B411**, 173 (1997).
13. F. Halzen and A. Martin "Quarks and Leptons", John Wiley & Sons (1984).
14. L. Holström *et al.*, Comp. Phys. Comm. **88**, 195 (1995).