Fermi National Accelerator Laboratory

FNAL/C--91/286-E

DE92 004636

Search for Top Quark at Fermilab Collider

The CDF Collaboration

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

presented by K. Sliwa

Tufts University, Department of Physics
Medford, Massachusetts 02155

October 1991

* Presented at the *"4th International Symposium on Heavy Flavour Physics"*, Universite de Paris-Sud, Orsay, France, June 25-29, 1991.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

TUFTS CONF 91/#13-1-E
FERMILAB-CONF-91/286-E
CDF/PUB/HEAVYFLAVOR/PUBLIC/1583

SEARCH FOR TOP QUARK AT FERMILAB COLLIDER

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presented by Krzysztof Sliwa
Tufts University, Department of Physics
Medford, Massachusetts 02155 USA

ABSTRACT

The status of a search for the top quark with Collider Detector at Fermilab (CDF), based on a data sample recorded during the 1988-1989 run is presented. The plans for the next Fermilab Collider run in 1992-1993 and the prospects of discovering the top quark are discussed.

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i. Introduction

The CDF limit on the mass of the top quark has not changed significantly from the one presented over a year ago[2]. This is not because of lack of effort, simply, CDF has not accumulated any new data since the 1988-1989 run ended. Many systematic effects have been studied in detail, most importantly the total luminosity is now understood with uncertainty reduced by more than a factor of two (6.8 % now as opposed to 15% a year ago). A combined analysis of dilepton and e+multijet+$\not{E}_t$ events, which led to the most stringent limit on the mass of the top quark, has been extended beyond the central region of the CDF detector to include the plug. However, the effect of increased acceptance has been almost exactly cancelled by the decrease of the total luminosity (from 4.4 pb^{-1} to 4.1 pb^{-1}) and the CDF limit on the mass of the top quark remains almost unchanged. Because the final details of this new analysis are still being discussed, the results presented at this conference correspond to the status of analysis as of Moriond 90', where the combined, from the di-leptons and low-P_t searches, upper limit on top quark mass $M_t >$ 89 GeV/c^2 @ 95% C.L. has been presented. (The final limit is only slightly better, $M_t >$ 90-91 GeV/c^2 @ 95% C.L.).

ii. Published CDF searches for $t\bar{t}$

At Fermilab Tevatron energy, $\sqrt{s} = 1.8$ TeV, the dominant production mechanism of top quarks is the production of $t\bar{t}$ pairs from a quark-antiquark or a gluon-gluon initial state through the strong interactions.

CDF has published[3-4] results from two searches for the top quark, and preliminary results of analysis which combined several decay modes has been presented at various conferences.

An analysis[3] of e+multijet+$\not{E}_t$ events was based on the fact that, for top quark mass smaller than W mass, the transverse mass distribution of the e+$\not{E}_t$ system, $M_t^{e\nu}$, is softer for $t\bar{t}$ than for W+jets events. The observed distributions were found consistent with W boson production. The resulting upper limit on the $t\bar{t}$ cross section excluded a Standard Model top quark mass in the range 40 GeV/c^2 $< M_t <$ 77 GeV/c^2. It is important to note this method loses its sensitivity with M_t approaching M_W, in which case the $M_t^{e\nu}$ distributions become indistinguishable.

The other published analysis[4] searched for high transverse energy e+μ events, in which final state the background from other processes is very small. One candidate event was found. Translating a limit on $t\bar{t}$ cross section found in this analysis yielded a limit on top quark mass of $M_t >$ 72 GeV/c^2.

iii. Search for $t\bar{t}$ in dilepton and e+multijet+$\not{E}_t$ events

In a natural extension of those two analyses additional decay modes were studied.

Dilepton analysis searched for events in which both top quarks decayed leptonically, for example $t \rightarrow e^+\nu_e b$ and $\bar{t} \rightarrow e^-\bar{\nu}_e\bar{b}$. Such events have a spectacular signature of two high transverse energy (E_t) leptons accompanied with missing transverse energy ($\not{E}_t$) and possibly soft b-quark jets.

If one of the top quarks decays leptonically, $t \rightarrow be^{+}\nu_e$, and the other hadronically, $\bar{t} \rightarrow \bar{b}q\bar{q}$, the final state will be that of an e+multijet+$\not{E}_t$ event. The two quark jets from a W decay would be highly energetic, while the b-jets should be softer. In an attempt to tag one of the two b-jets a presence of an additional soft lepton was required.

The results of di-lepton and e+multijet+$\not{E}_t$+b-tag were combined. With increased acceptance, a more stringent limit on the mass of the top quark has been derived.

Dilepton search for $t\bar{t}$

In the central region ($|\eta| < 1.0$ for $e^{\pm}$ and $|\eta| < 1.2$ for $\mu^{\pm}$; $|\eta|$ - pseudorapidity), measuring the electron and muon parameters region is well understood and the knowledge of systematic errors is very good. CDF has analysed the high transverse energy $e^{+}e^{-}$ and $\mu^{+}\mu^{-}$ pairs in the central region, removing $Z^{o} \rightarrow e^{+}e^{-}$ and $Z^{o} \rightarrow \mu^{+}\mu^{-}$ candidates. The e+μ channel has been reanalysed with the same cuts as for the other di-lepton channels. The details of event selection, in its lepton identification part, follow the e+μ analysis[4]. Events with opposite charge electrons or muons, and with $E_t^e > 15$ GeV and $P_t^{\mu} > 15$ GeV/c[2] were selected. In the $e^{+}e^{-}$ and $\mu^{+}\mu^{-}$ events the Z^{o} events were removed with the help of:

a) a cut on the di-lepton mass, 75 GeV/c^2 > $M_{l^+l^-}$ > 105 GeV/c^2;
b) a missing transverse energy cut, $\not{E}_t > 20$ GeV;
c) a cut on the azimuth angle between the leptons, $20^{o} < \Delta\phi_{l^+l^-} < 160^{o}$.

In Figure 1 we present the $M_{e^+e^-}$ and $\not{E}_t$ distributions for a large sample (730 pb^{-1}) of $t\bar{t}$ Monte Carlo data with M_t=90 GeV/c^2, and for CDF di-electron events. Figure 2 shows the $\Delta\phi_{e^+e^-}$ distributions, and scatterplots of $\Delta\phi_{e^+e^-}$ vs $\not{E}_t$, after $M_{e^+e^-}$ cut, for Monte Carlo and data. No events pass the $M_{e^+e^-}$,$\Delta\phi$ and $\not{E}_t$ cuts. Figure 3 shows the analogous $\Delta\phi_{l^+l^-}$ vs $\not{E}_t$ scatterplots for the $\mu^{+}\mu^{-}$ and $e^{\pm}\mu^{\mp}$ events. No $\mu^{+}\mu^{-}$ events and one, already known[4], eμ event is found after the $M_{l^+l^-}$,$\Delta\phi$ and $\not{E}_t$ cuts are applied. The kinematics characteristics of the eμ candidate event is presented in Table I.

Table II summarizes, as a function of top quark mass, the experimental acceptances (studied with ISAJET 6.21 and full CDF detector simulation Monte Carlo), $t\bar{t}$ cross section[5] and the expected number of events in 4.4 pb^{-1}. The total systematic error for the three di-lepton channels combined was 20%. The branching fraction of 4/81 has been assumed. The most important systematic error in the di-lepton analysis were uncertainty in luminosity (15%) and P_t spectrum uncertainties (10%).

After convoluting[6,7,8] the 20% systematic error with a Poisson distribution a 95% C.L. upper limit of 5.16 events for a number of $t\bar{t}$ events seen with CDF in the di-lepton channels has been found. An upper limit on the $t\bar{t}$ cross section translates, when compared with the results of a theoretical calculation in the framework of the Standard Model[5], into a limit on the mass of the top quark, $M_t > 84$ GeV/c^2 @ 95% C.L.

Low-P_t muon search

A new technique was used to analyse the e+multijet and μ+multijet events, which could occur when one of the top quarks quark decays leptonically and the other hadronically, leading to a lepton+$\not{E}_t$+4jets final state. Selection cuts in electron+multijet case are virtually identical to those used in e+jets top search[3]. A sample of 105 events was selected by requiring $\not{E}_t$ >20 GeV, E_t^e >20 GeV, and at least two jets with E_t^j >10 GeV and within $|\eta| < 2.0$. The muon+multijet sample consisted of 87 events, with jet and $\not{E}_t$ cuts as in electron+multijet channel, and $P_t^\mu >$ 20 GeV/c^2. A new technique used here makes an attempt to tag one of the two b-quark jets by requiring a low transverse momentum muon to be well isolated from any of the two highest E_t jets, ΔR >0.5, $\Delta R \equiv [(\Delta\eta)^2 + (\Delta\phi)^2]^{1/2}$. (According to a Monte Carlo study muons from b-jets have $P_t^\mu <$ 15 GeV/c^2.) Figure 4 shows the distributions of ΔR between the low-P_t muon and the nearest, in R space, of the two highest E_t jets for a) 250 pb^{-1} Monte Carlo $t\bar{t}$ events generated with M_t=90 GeV/c^2, and b) 4.4 pb^{-1} CDF data. No candidates were found.

In Table II we present, as a function of top quark mass, the experimental acceptance and the expected number of events in 4.4 pb^{-1} for the low-P_t search. The combined branching fraction of 10.9% was assumed (2/3×2/9×2×(probability of any of the two b-quarks to decay into a μ)=8/27×0.37). The combined systematic error was 25%, with the largest contributions being the uncertainty in luminosity (15%), Monte Carlo statistics (12%) and B semileptonic branching fractions (9.4%)

iii. Evaluation of a combined upper limit

Suppose one performs an analysis in m channels, with ϵ_i being an efficiency for observing $t\bar{t}$ events in each of the modes. The probability of observing n_i^o events in i-th channel is given by a likelihood function $L \equiv \prod_{i=1}^{m} P(n_i^o; \epsilon_i N_{t\bar{t}}$, where $\epsilon_i N_{t\bar{t}})$ is the mean number of events expected in the i-th channel, and $P(n;\mu)$ is Poisson probability distribution function with the mean μ. Solving for $\overline{N_{t\bar{t}}}$ that maximizes L, one finds: $\overline{N_{t\bar{t}}} = \sum_{i=1}^{m} n_i^o / \sum_{i=1}^{m} \epsilon_i$. To incorporate the systematic uncertainties we use a standard procedure[6,7,8], where the correlations in uncertainties of acceptances were properly taken into account. Figure 5 shows the upper limits on the $t\bar{t}$ cross section superimposed on the results of a theoretical calculation based on the Standard Model[5]. The combined upper limit on the $t\bar{t}$ cross section, from the di-leptons and low-P_t searches, leads to a lower limit on top quark mass $M_t >$ 89 GeV/c^2 @ 95% C.L.

iv. Physics reach of the future 1992-1993 Fermilab Collider run

The next physics run with Fermilab Collider is supposed to begin in March 1992. For those familiar with Fermilab schedule it means perhaps only that it will not begin before this date. With no more SppS runs, Fermilab's CDF and D0. are in a special position of being the only two experiments which may find the top quark in the near future.

D0 will have it's first physics run in 1992. Compared with CDF it has superior μ coverage and good electromagnetic and hadronic calorimetry in a broader rapidity range. On the other hand, it does not have a magnetic field making particles' momentum and charge determination from tracking impossible. A crude momentum measurement is only available for μ, in D0 magnetized iron toroids outside the calorimeters. However, CDF has demonstrated that the signatures of possible $t\bar{t}$ production are spectacular and clean, and it seems that D0 detector can do as well as CDF, if not better because of it's better acceptance, in a search for top quark in the $e\mu$ channel.

CDF is extending it's μ coverage in preparation for the next run. Also, it's new silicon vertex detector may prove essential for attempts to tag the b-jets from $t, \bar{t}$ decays.

Having two detectors, implementing different, and in the same time complementary, conceptual approach to detection of high energy physics processes may become very important if, say, more $e\mu$ events are detected next year. It is relatively simple to set an upper limit, as shown in this paper. To *prove* that the observed events are *indeed* due to $t\bar{t}$ production is more difficult. One would have to confirm the characteristics expected for $t\bar{t}$ events in, most desirably, several independent channels.

Another reason why analysis becomes more difficult with increasing top mass is the phase space suppression. The higher the top quark mass the smaller the $t\bar{t}$ production cross section. The backgrounds from other processes, even if found small so far in CDF searches, may overwhelm the possible signal. Let us recall, as an example, that for M_t=150 GeV the cross section for $t\bar{t}$ production is equal to that for W^+W^- production. A search for $e\mu$ events from $t\bar{t}$ will inevitably find an equal number of such events, with quite similar characteristics, from direct di-boson production.

The plan for the next Collder run is to accumulate events corresponding to about 100 pb^{-1}. The run may be divided into two parts, and in such a case 25 pb^{-1} are expected to be collected in the first running period.

Assuming no new candidates are found, the single most important factor in estimating how far CDF and D0 will be able to push the lower limit on the mass of the top quark is the integrated luminosity. The upper bound on the $t\bar{t}$ cross section corresponding to one event (the $e\mu$ candidate found in the last CDF run) would mean $M_t > 120$ GeV/c^2 for an integrated luminosity of 25 pb^{-1}; $M_t > 160$ GeV/c^2 for a luminosity of 75 pb^{-1} and $M_t > 170$ GeV/c^2 for a luminosity of 100 pb^{-1}. (The above estimate may prove slightly conservative, since CDF is extending it's μ acceptance, and D0 detector has a good μ coverage already.)

Alterelli[9] has presented at this conference the most up-to-date results of a "consistency check" of the Standard Model. The mass of the top quark is now (compiling all available measurements and assuming the validity of the Standard Model) expected to be in the range $M_t \in (95,190)$ GeV, with the central value of predictions varying with the Higgs mass, namely, $M_t \approx 115$ GeV for a light Higgs and $M_t \approx 150$ GeV for a heavy Higgs. This is *within* the reach of the 100 pb^{-1} run. Let the beams collide !

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TABLE I: **Characteristics of the CDF $e\mu$ candidate event, Run 19250, event 20425. (Jet energies are the corrected energies, the uncorrected energies are listed in paranthesis for the sake of completeness.)**

	charge	E_T (GeV)	η	ϕ radians
central electron	+	31.72	-0.81	2.30
central muon	-	42.54	-0.80	4.70
forward muon	+	7.58	-1.96	1.70
jet 1		19.73 (12.56)	1.07	5.96
jet 2		8.89 (5.0)	-2.76	1.49

TABLE II: **$t\bar{t}$ cross section, acceptance×branching fractions, and predicted number of events in 4.4 pb^{-1} for the di-leptons and low-P_t muon analyses.**

Top mass (GeV/c^2)	$\sigma(t\bar{t})$ (pb)	acc×BF (di-leptons)	#events (di-leptons)	acc×BF (low-P_t μ)	#events (low-P_t μ)
75	385	.00605	10.2	.00152	2.6
80	285	.00709	8.9	.00181	2.3
85	200	.00746	6.6	.00228	2.0
90	153	.00774	5.2	.00233	1.6

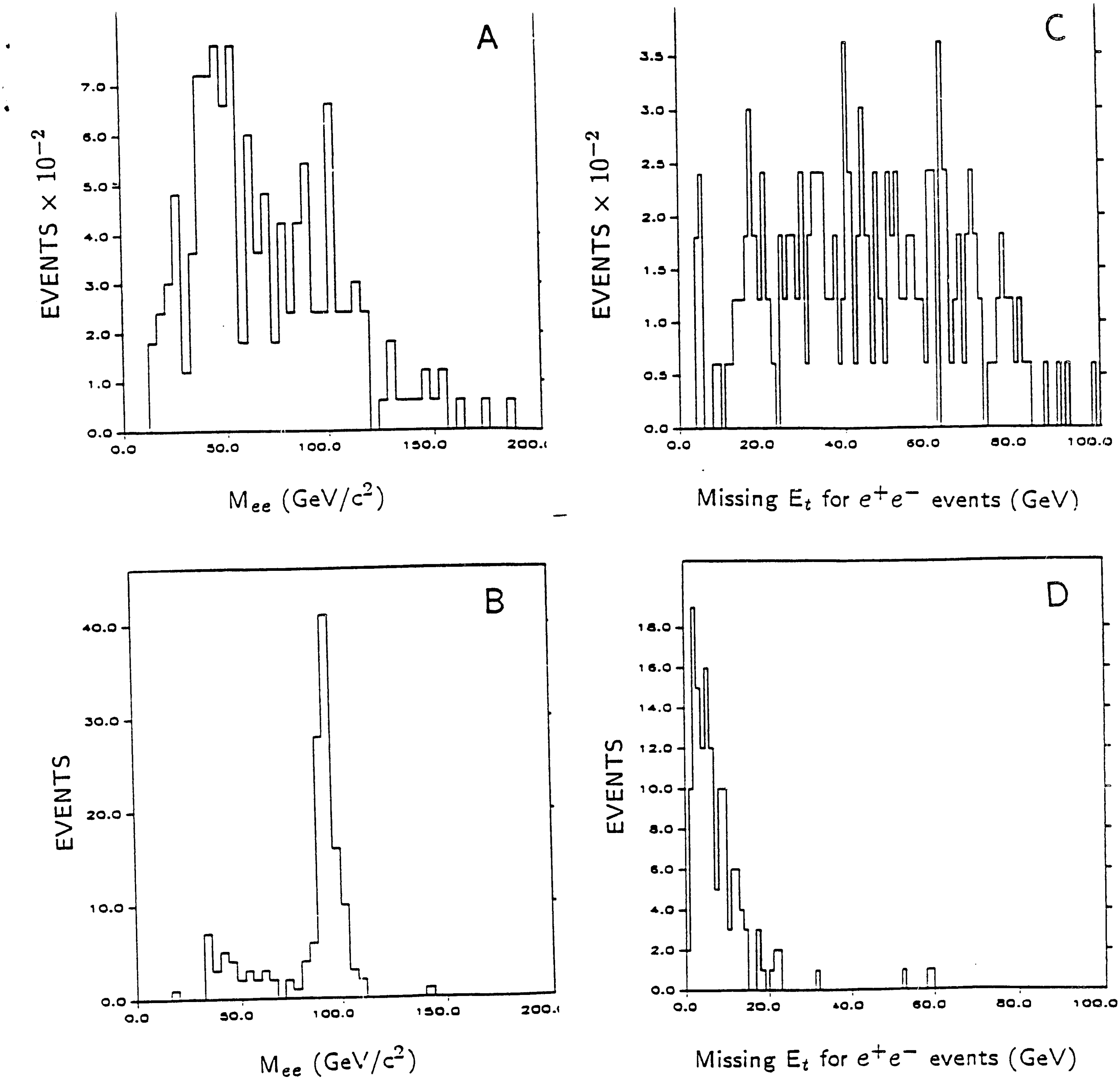

Figure 1. a) e^+e^- mass distribution for electrons with transverse energy $\not{E}_t > 15$ GeV from a 730 pb^{-1} sample of Monte Carlo $t\bar{t}$ events generated with top quark mass of 90 GeV/c^2; b) e^+e^- mass distribution for electrons with $\not{E} > 15$ GeV from a 4.4 pb^{-1} CDF data sample, Z^o peak is clearly visibile; c) missing transverse energy ($\not{E}_t$) distribution for e^+e^- events from a 730 pb^{-1} sample of Monte Carlo $t\bar{t}$ events generated with M_t=90 GeV/c^2; d) $\not{E}_t$ distribution for e^+e^- events from CDF data.

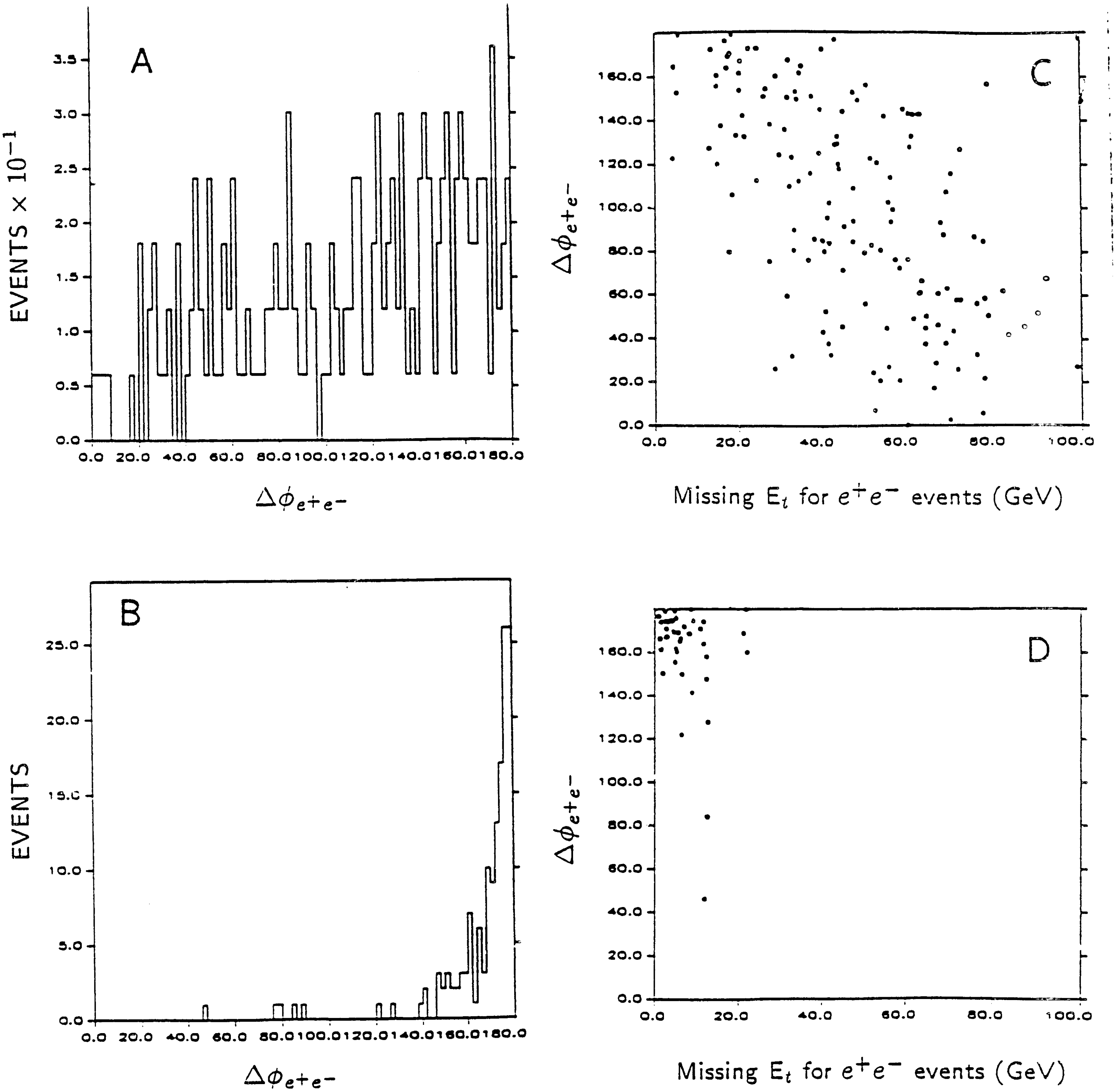

Figure 2. a) Distribution of the azimuth angle, $\Delta\phi_{e^+e^-}$, between the two electrons from a 730 pb^{-1} sample of Monte Carlo $t\bar{t}$ events generated with top quark mass of 90 GeV/c^2; b) $\Delta\phi_{e^+e^-}$ distribution for CDF data sample; c) $\Delta\phi_{e^+e^-}$ vs $\not{E}_t$ scatterplot for 90 GeV/c^2 top quark Monte Carlo events, after a $M_{e^+e^-}$ cut to remove Z^o events; d) $\Delta\phi_{e^+e^-}$ vs $\not{E}_t$ scatterplot for CDF data, Z^o events removed.

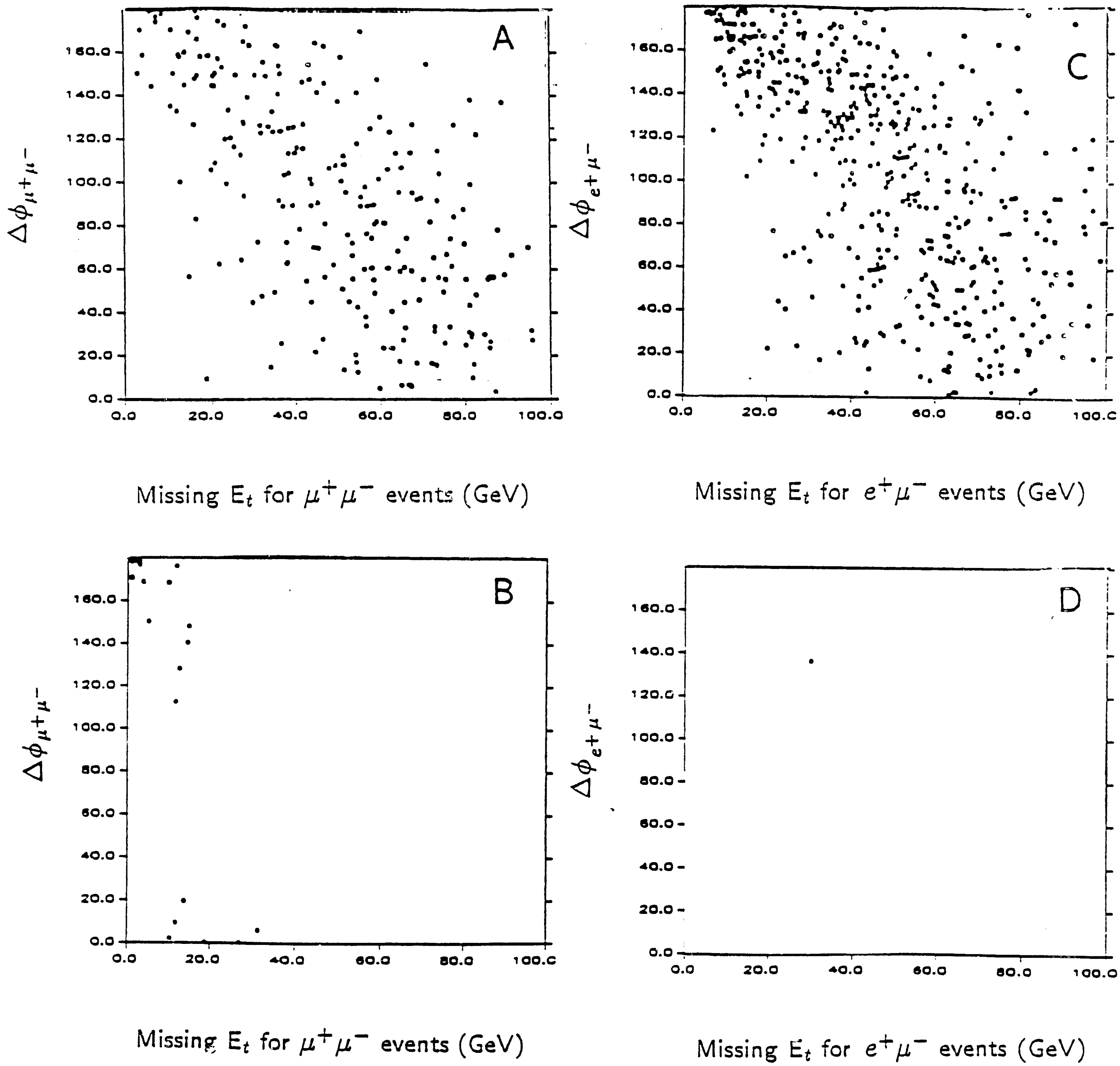

Figure 3. a) $\Delta\phi_{\mu^+\mu^-}$ vs $\not{E}_t$ scatterplot for 90 GeV/c^2 top quark Monte Carlo events, after a $M_{\mu^+\mu^-}$ cut to remove Z° events; b) $\Delta\phi_{\mu^+\mu^-}$ vs $\not{E}_t$ scatterplot for CDF data, Z° events removed. c) $\Delta\phi_{e^+\mu^-}$ vs $\not{E}_t$ scatterplot for 90 GeV/c^2 top quark Monte Carlo events, after a $M_{e^+\mu^-}$ cut; d) $\Delta\phi_{e^+\mu^-}$ vs $\not{E}_t$ scatterplot for CDF data, after a $M_{e^+\mu^-}$ cut.

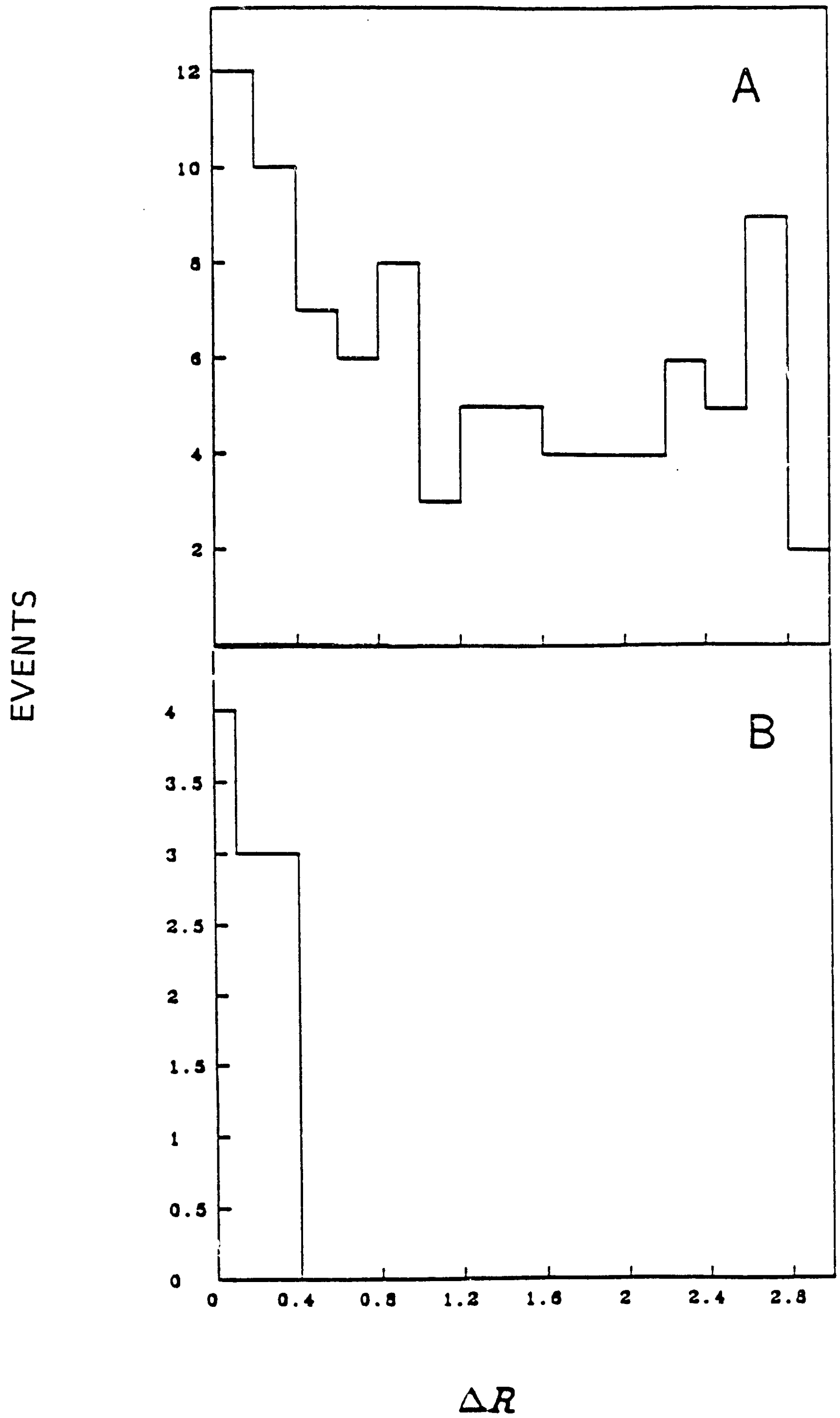

Figure 4. The distributions of ΔR, $\Delta R \equiv [(\Delta\eta)^2+(\Delta\phi)^2]^{1/2}$. between the low-$P_t$ muon and the nearest, in R space, of the two highest E_t jets for a) 250 pb^{-1} Monte Carlo $t\bar{t}$ events generated with M_t=90 GeV/c^2, and b) 4.4 pb^{-1} CDF data.

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