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A New Limit on the Mass of the Top Quark*

The CDF Collaboration

presented by

Krzysztof Sliwa
Tufts University
Medford, Massachusetts 02155

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A NEW LIMIT ON THE MASS OF THE TOP QUARK

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Tufts University, Department of Physics
Medford, Massachusetts 02155 USA

ABSTRACT

We present a preliminary result of an extension of our already published search for the top quark. The analysis is based on a data sample recorded during the 1988-1989 run with Collider Detector at Fermilab (CDF), and corresponding to an integrated luminosity of 4.4 pb^{-1}. In addition to the previously studied events with energetic $e^{\pm}\mu^{\mp}$ pairs we have analysed the two remaining di-lepton channels, namely, $e^{+}e^{-}$ and $\mu^{+}\mu^{-}$. A new search was performed in electron+multijet and muon+multijet events, in which an additional low-transverse-momentum μ was required as a signature of a b-quark jet. No new candidates were found. A combined upper limit on the $t\bar{t}$ cross section, derived from these samples, translates, in the context of the Standard Model, into a limit on the mass of the top quark, $M_t > 89$ GeV/c^2 @ 95% C.L. Top quarks can thus decay into the $W^{\pm}$+quark final states in which a $W^{\pm}$ is an on-mass-shell particle.

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i. Introduction

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 two-gluon initial state through the strong interactions.

Leptonic decays of both top quarks, for example: $t \rightarrow e^+\nu_e b$ and $\bar{t} \rightarrow e^-\bar{\nu}_e\bar{b}$, lead to events with 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.

CDF has published results from two searches for the top quark. An analysis[2)] of e+multijet+$\not{E}_t$ events found those to be consistent with W boson production. The dominant source of background to the possible $t\bar{t}$ signal comes from the W+two-jet process of QCD. The analysis 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 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. This method loses its sensitivity with M_t approaching M_W, in which case the $M_t^{e\nu}$ distributions become indistinguishable.

The other analysis[3)] searched for the high transverse energy e+μ events, in which final state the background from other processes is very small. One candidate event was found. A limit on $t\bar{t}$ cross section derived from this channel translates into a limit on top quark mass of $M_t > 72$ GeV/c^2.

We present here a preliminary result of a natural extension of previous analyses. Additional decay modes were studied and, with increased acceptance, a more stringent limit on the mass of the top quark has been derived.

ii. Dilepton search for $t\bar{t}$

This analysis is a straight-forward extension of the high transverse energy e+μ pairs search. Measuring the electron and muon parameters in the central region ($|\eta| < 1.0$ for $e^\pm$ and $|\eta| < 1.2$ for $\mu^\pm$; $|\eta|$ being the pseudorapidity) is well understood and the knowledge of systematic errors is very good. We have 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[3)]. Events with opposite charge electrons or muons, and with $E_t^e > 15$ GeV and $P_t^\mu > 15$ GeV/c^2[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[3]), $e\mu$ event is found after the $M_{l^+l^-}$,$\Delta\phi$ and $\not{E}_t$ cuts are applied. (An excess of di-muon events with small $\Delta\phi$ and $\not{E}_t$ is due to the finite probabilities of a) particles in jets to decay into muons and b) misidentification because of punchthrough, combined with an abundance of high energy multijet events.) Table I 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[4]), the expected number of events in 4.4 pb^{-1}, and the total systematic error for the three di-lepton channels combined. The branching fraction of 4/81 has been assumed. The most important systematic errors in the di-lepton analysis are listed, together with those in the low-P_t μ analysis, in Table II. After convoluting[5,6,7]) the 20% systematic error with a Poisson distribution we find 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. 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[4]), into a limit on the mass of the top quark, $M_t > 84$ GeV/c^2 @ 95% C.L.

iii. Low-P_t muon search

A new technique was used to analyse the e+multijet and μ+multijet events. Such events 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. The two quark jets from a W decay would be highly energetic, while the b-jets should be softer. Selection cuts in electron+multijet case are virtually identical to those used in e+jets top search[2]). 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. To derive a limit on cross section a careful tuning of Monte Carlo simulation was performed. (ISAJET 6.22 and full CDF detector simulation CDFSIM were used.) The ratio of D/D* in b-quark decays was fixed to 28/72 based on the most recent CLEO results[8]. In Table I we present, as a function of top quark mass, the experimental acceptance, the expected number of events in 4.4 pb^{-1} and the total systematic error 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 largest systematic errors are listed in Table II.

iv. 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 the standard procedure[5,6,7], where the correlations in the 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[4]. 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.

REFERENCES

1. The CDF Collaboration consists of the following institutions: Argonne National Laboratory, Brandeis University, University of Chicago, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati (INFN), Harvard University, University of Illinois, National Laboratory for High Energy Physics (KEK), Lawrence Berkeley Laboratory, University of Pennsylvania, INFN University and Scuola Normale Superiore of Pisa, Purdue University, Rockefeller University, Rutgers University, Texas A&M University, University of Tsukuba, Tufts University and University of Wisconsin.
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TABLE I: $t\bar{t}$ **cross section, acceptance×branching fractions, total systematic errors, 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	$\sum\sigma_{sys}$ di-leptons	#events	acc×BF	$\sum\sigma_{sys}$ low-P$_t$ μ	#events
75	385	.00605	20%	10.2	.00152	25%	2.6
80	285	.00709	20%	8.9	.00181	25%	2.3
85	200	.00746	20%	6.6	.00228	25%	2.0
90	153	.00774	20%	5.2	.00233	25%	1.6

TABLE II: Systematic errors for the low-P$_t$ μ and di-lepton searches for the top quark.

systematic effect	di-leptons	low-P$_t$ μ
luminosity	15%	15%
Monte Carlo statistics	5%	12%
P$_t$ spectrum uncertainties	10%	5%
B semileptonic branching fraction	-	9.4%
low P$_t$ μ acceptance	-	5%
jet counting due to E$_t$ scale	-	5%
top fragmentation	5%	5%
B fragmentation	-	5%
high P$_t$ lepton efficiency	4%	4%
acceptance (ISAJET vs Papageno)	4%	2%
$\not{E}_t$ uncertainty	2%	-
errors uncorrelated to the other analysis	5.4%	18.1%
errors correlated to the other analysis	18.9%	17.2%
total systematic error	19.7%	25%

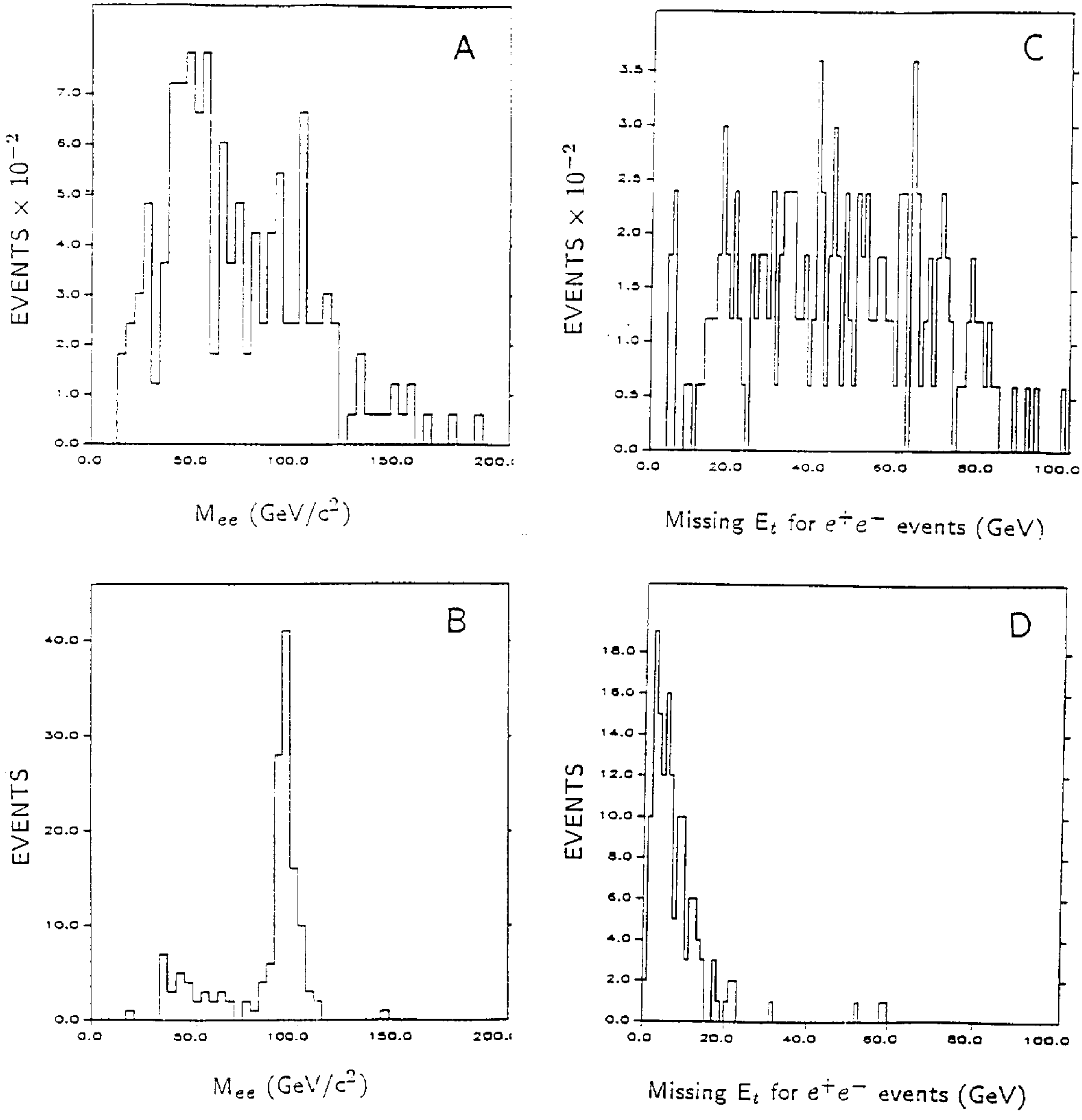

Figure 1. a) e^+e^- mass distribution for electrons with transverse energy $\not{E}_t > 15$ GeV from a 730 pb^{-1} sample of Monte Carlo $t\bar{t}$ events generated with top quark mass of 90 GeV/c^2; b) e^+e^- mass distribution for electrons with $\not{E} > 15$ GeV from a 4.4 pb^{-1} CDF data sample,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

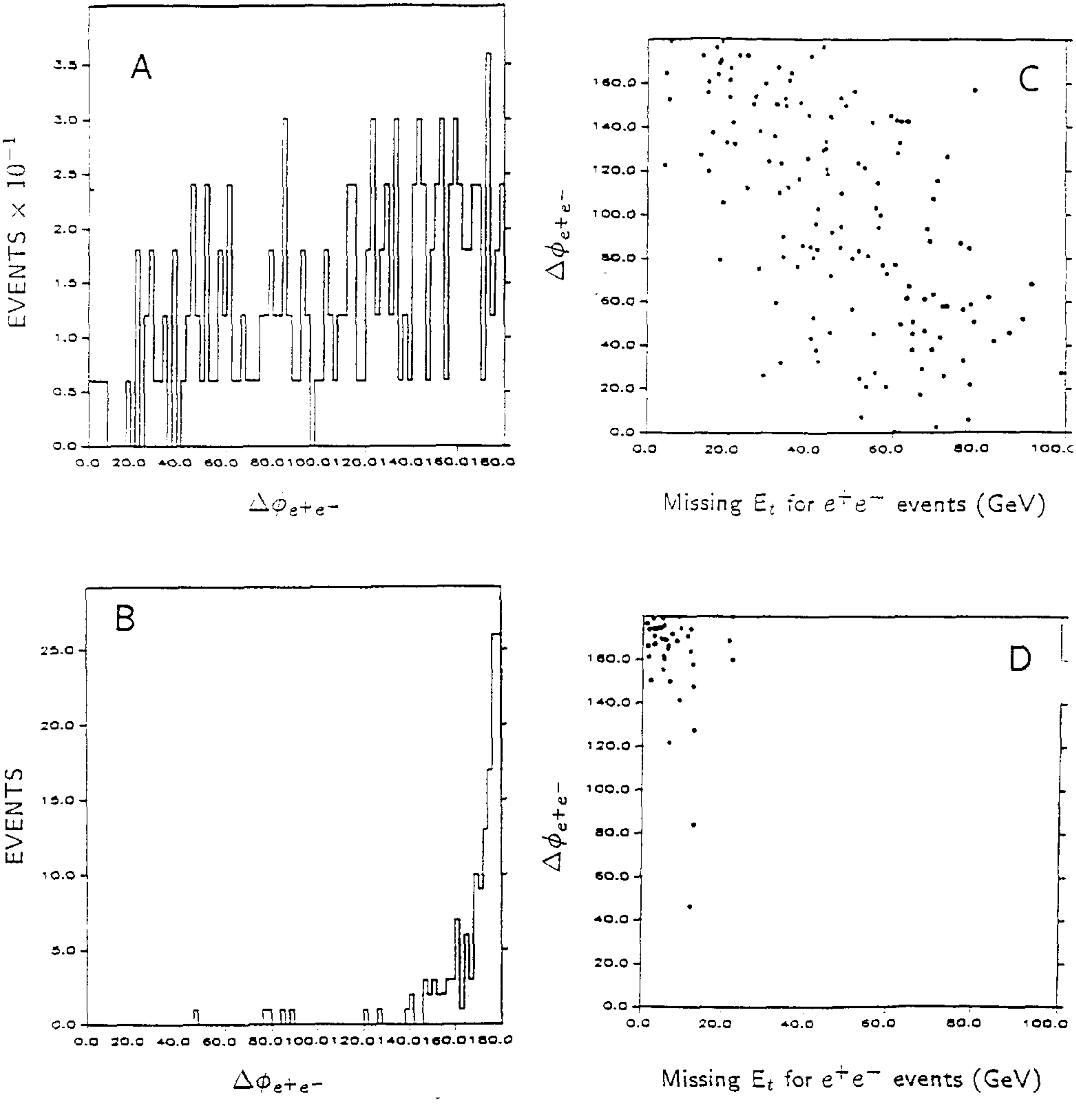

Figure 2. a) Distribution of the azimuth angle, $\Delta\phi_{e^+e^-}$, between the two electrons from a 730 pb^{-1} sample of Monte Carlo $t\bar{t}$ events generated with top quark mass of 90 GeV/c^2; b) $\Delta\phi_{e^+e^-}$ distribution for CDF data sample; c) $\Delta\phi_{e^+e^-}$ vs $\not{E}_t$ scatterplot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

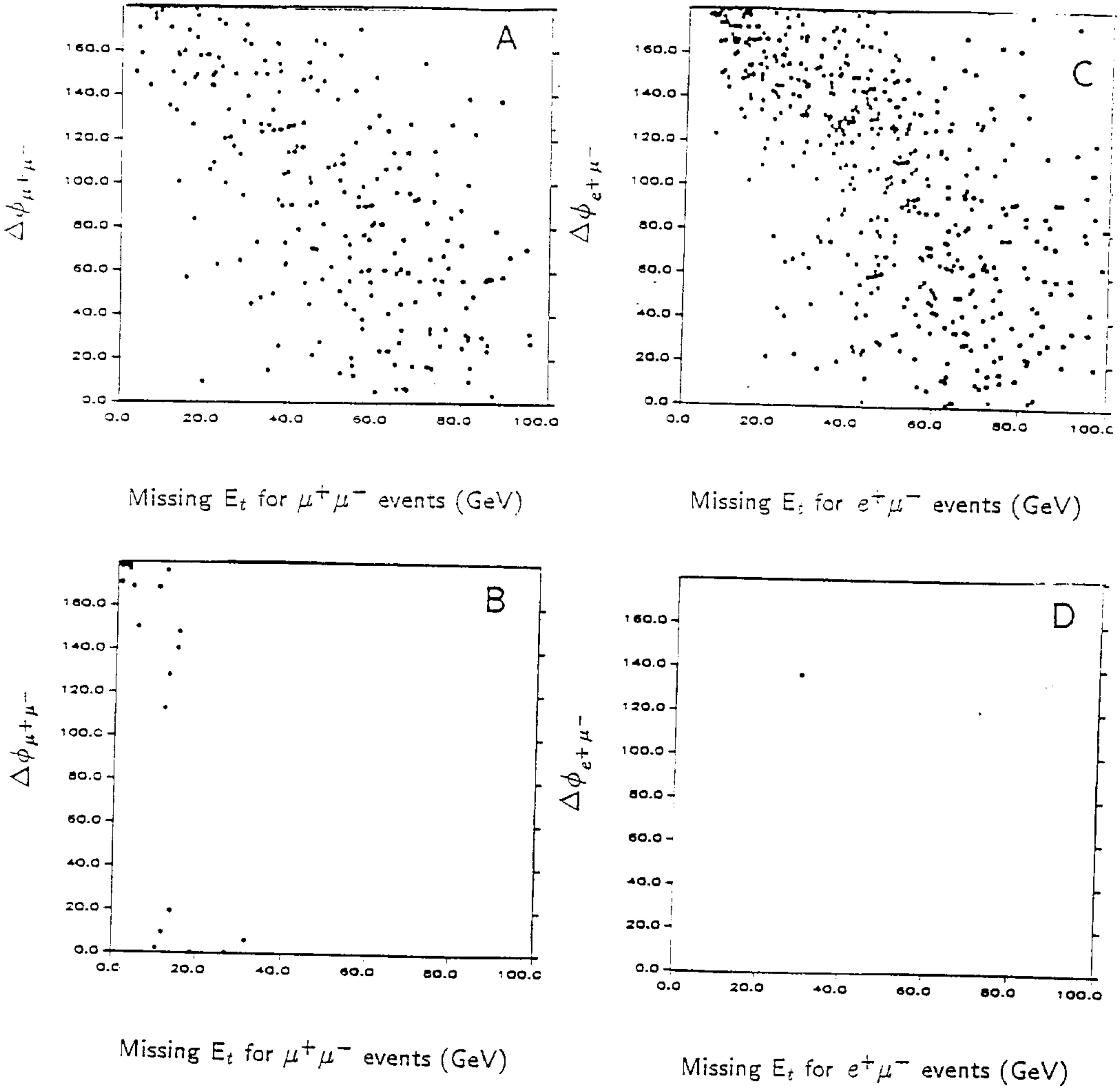

Figure 3. a) $\Delta\phi_{\mu^+\mu^-}$ vs $\not{E}_t$ scatterplot for 90 GeV/c^2 top quark Monte Carlo events, after a $M_{\mu^+\mu^-}$ cut to remove Z^o events; b) $\Delta\phi_{\mu^+\mu^-}$ vs $\not{E}_t$ scatterplot for CDF data, Z^o events removed. c) $\Delta\phi_{e^+\mu^-}$ vs $\not{E}_t$ scatterplot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

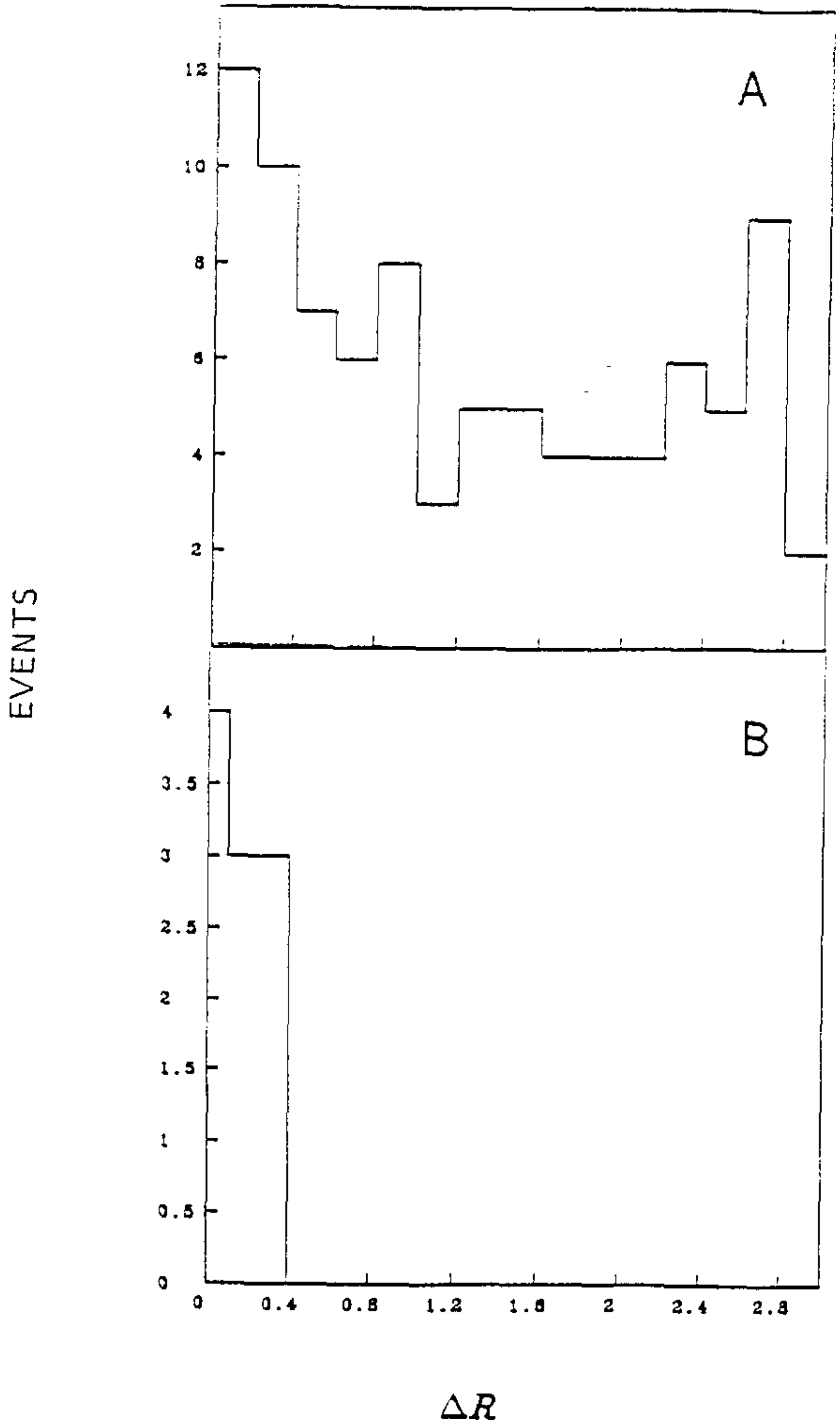

Figure 4. The distributions of ΔR, $\Delta R \equiv [(\Delta\eta)^2+(\Delta\phi)^2]^{1/2}$. between the low-$P_t$ muon and the neares in R space, of the two highest E_t jets for a) 250 pb^{-1} Monte Carlo $t\bar{t}$ events generated wi M_t=90 GeV/c^2, and b) 4.4 pb^{-1} CDF data.

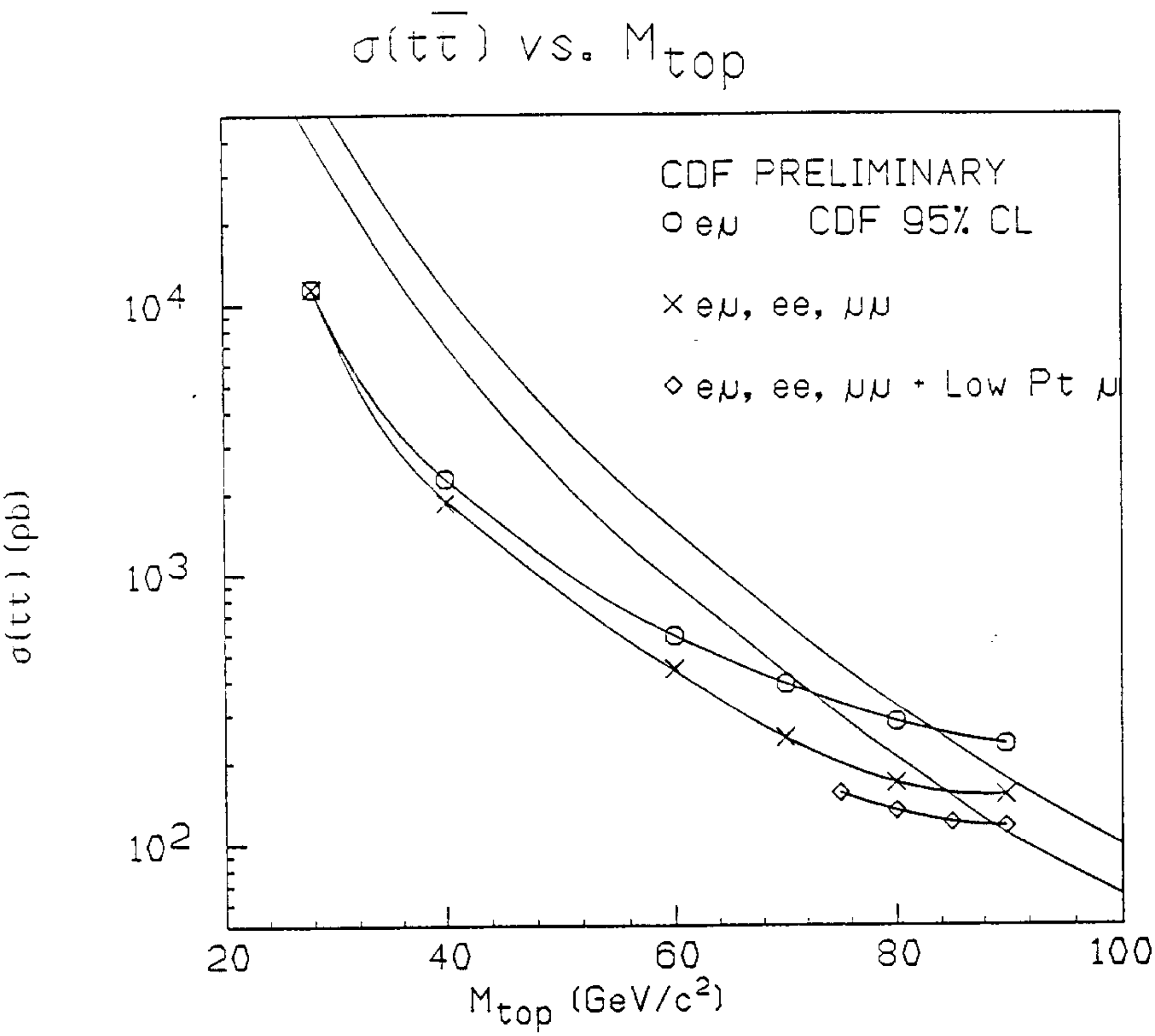

Figure 5. Experimental upper limits on $t\bar{t}$ cross section (@ 95% C.L.) as a function of top quark mass, based on searches described in this paper. Superimposed are the upper and lower bounds of the prediction from a Standard Model theoretical calculation[4)]. The limits on the mass of the top quark are derived by finding an intersection of the experimental upper limit curve with the theoretical *lower* bound for the $t\bar{t}$ cross section.