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Search for the Top Quark from (e, μ) and (e, e) Events in the DØ Detector in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

We present results from searches for top quark production in $p\bar{p}$ collisions at the Tevatron collider based on an integrated luminosity of 7.5 pb^{-1} obtained during the 1992-1993 run. The present results are confined to decay modes where both the top and anti-top quarks in the event decay semi-leptonically to the ee and $e\mu$ channels. A lower limit of 103 (99) GeV/c^2 is obtained at 95% confidence level for the top quark mass from the absence of events consistent with standard model top quark decays with background subtraction (no background subtraction). We do however observe one event in the $e\mu$ channel which cannot be explained by the known backgrounds. While we make no claim that this event is due to top quark decay, it is not inconsistent with a top quark mass in the range $130 - 170\, GeV/c^2$

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I. INTRODUCTION

The standard model [1,2] requires the existence of the top quark to complete the three generations of quarks and leptons. Lower bounds up to 91 GeV/c^2 have been reported [3–6] for the top quark mass and precision measurements of electroweak parameters predict the mass of the top quark to be $152 \pm 17 \pm 21$ GeV/c^2, [7] which assumes the completeness of the standard model . The dominant mode of top quark production at the Tevatron is via parton fusion into $t\bar{t}$ [8–10]. Since the top quark is now established to be heavier than the W boson, each top quark will decay into a real W. Each W then decays leptonically into a charged lepton and neutrino or hadronically into a pair of quarks. The branching ratio for both W's from a $t\bar{t}$ pair to decay into an $e\mu$ pair is $\frac{2}{81}$ and into an ee pair is $\frac{1}{81}$. The channels where both the W's decay leptonicaly is relatively background free and we choose to study these channels in this paper. The signature for a top quark event then is two high p_T leptons accompanied by at least two jets (from the decay of the associated b quark) and significant missing transverse momentum due to the emission of undetected neutrinos from the W decay.

The DØ detector [12] is particularly suited to the detection of these event signatures. The highly segmented , hermetic uranium liquid argon calorimeter with its stable calibration is well suited to detecting electrons (fractional energy resolution $(\sigma/E)^2 = (0.003)^2 + (0.157)^2/E + (0.29)^2/E^2$) and jets ($\sigma/E = 80\%/\sqrt{(E)}$) in the pseudo-rapidity range $|\eta| < 3.2$. The hermeticity of the calorimeter is typified by the fact that the coverage extends to pseudo-rapidities of 4.5. The nearly 4π coverage afforded by the muon system enables us to detect muons with p_T greater than 3.0 GeV/c down to angles of 3 degrees with respect to the beam line with fractional momentum resolution of $\delta p/p = 0.2 + 0.01p$. Our missing E_T resolution is excellent by virtue of the hermeticity of the calorimetry and has been parametrized [12] by $\sigma E_T = 1.08 + 0.019\ \Sigma E_T$.

II. ee EVENT SELECTION

DØ is triggered by two scintillator hodoscopes (level 0) placed ± 140 *cm* on either side of the interaction region which capture 97% of all non-diffractive inelastic interactions. The minimum-bias trigger resulting from this is pre-scaled and written to tape and is used to calculate the integrated luminosity of the experiment using previously measured minimum bias cross sections [11], corrected for multiple interactions using the instantaneous luminosity. The total integrated luminosity being reported here for the *ee* channel is $7.3 \pm 0.88\ pb^{-1}$.

A customized electronic trigger logic (level 1) [12] then determines the E_T deposited in calorimeter towers of 0.2×0.2 in $\Delta\eta \times \Delta\phi$, where η, ϕ are the pseudo-rapidity and azimuthal angle (in radians) coordinates. The muon trigger is formed at level 1 from patterns of latched muon chamber drift cells which correspond to preprogrammed roads consistent with muons coming from the interaction region. The events that pass the level 1 criteria are then processed in a farm of micro-vaxes (level 2) [12] where more sophisticated algorithms are applied on the electromagnetic clusters and jets, and the muon momentum and missing transverse momentum are more accurately determined for the event. For electrons used in this analysis, we demand the logical OR of three level 1 trigger and level 2 conditions. 1) One level 1 electromagnetic(EM) tower with $E_T > 14$ GeV which produces an isolated level 2 electron candidate with $E_T > 20$ GeV and level 2 missing $E_T > 20$ GeV. 2)Two level 1 EM towers with $E_T > 7$ GeV and two isolated electron candidates with $E_T > 20$

GeV at level 2 3) One level 1 EM tower with $E_T > 20$ GeV , two level 1 jet towers with $E_T > 5$ GeV leading to one level 2 electron candidate with $E_T > 15$ GeV , two level 2 jets with $E_T > 16$ GeV and level 2 missing $E_T > 20$ GeV. In this trigger , an electron may simultaneously satisfy level 1 electron and jet conditions.

The offline event selection cuts were chosen to retain good efficiency for top decays while minimizing backgrounds. We impose covariance matrix conditions on the shape of the calorimeter electron energy deposition ($\chi^2 < 200$) which were determined from test beam data [13]. We also demand a good central detector track matched with the calorimeter centroid of the electron for one of the electrons. The offline cuts for the ee analysis thus demand two electrons with $E_T > 15$ GeV, missing $E_T > 20$ Gev and 2 jets with $E_T >$ 20 GeV. We also eliminate Z decays to electrons by removing electron pairs with effective mass $\pm 14\, GeV/c^2$ about the Z peak. Events with jets which deposit more than 40% of their energy in the Inter Cryostat detector are also removed from the sample. The efficiency of the calorimeter electron identification cuts has been determined to be 90% from W decays . The efficiency for track finding has been estimated to be 80% from $Z \to ee$ decays. Taking into account the correlation between the efficiencies of the trigger and offline cuts, we determine overall efficiencies for our ee event selection as a function of the top mass. These efficiencies are given in table I. Note that the efficiency for triggering and selection of ee candidates from $t\bar{t}$ decays goes up with top mass because the average energy of the electrons increases. The ee event selection efficiencies have an error of 15% on them which include systematic and statistical uncertainties.

III. $e\mu$ EVENT SELECTION

In this channel we have used an integrated luminosity of $7.5 \pm 0.9\ pb^{-1}$ using the three different trigger configurations: EM cluster + muon, EM cluster + $\geq$ 2jets and muon + $\geq$ 2jets. The following level 2 trigger requirements were imposed for the three configurations. One EM cluster $E_T > 7\,GeV$ and a muon with $p_T > 5\,GeV, |\eta| < 1.7$ for the EM cluster + muon channel; one EM cluster $E_T > 12\,GeV$ and two or more jets with $E_T > 16\,GeV$ and missing $E_T > 20\,GeV$ in the EM cluster $+\geq$ 2 jets channel; and a muon with $p_T > 5\,GeV, |\eta| < 1.7$, one jet with $E_T > 25\,GeV$, another jet with $E_T > 15\,GeV$ and missing $E_T > 12\,GeV$ in the muon + $\geq$ 2jets channel. Further offline requirements were imposed on the EM cluster, (covariance matrix $\chi^2 < 200$, $E_T > 15\,GeV$ with $|\eta| <2.5$) and the muon ($p_T > 15$ GeV and $|\eta| <1.7$) . Next we suppress backgrounds from non-top conventional processes by requiring that both leptons be isolated in the calorimeter and that the minimum $\eta - \phi$ separation , $\Delta R(\equiv \sqrt{(}\delta\phi^2 + \delta\eta^2))$ be at least 0.25 between the electron and the muon. These cuts remove a substantial fraction of the backgrounds from QCD multijet events and from radiative $W \to \mu\nu$ and $Z \to \mu^+\mu^-$ events. We then require that the missing $E_T >$ 20 GeV and at least two reconstructed hadronic jets of $E_T > 12$ GeV and 10 GeV . These cuts remove most of the backgrounds for $Z \to \tau^+\tau^-$ decays, $Z \to b\bar{b}$ decays and W^+W^- and WZ pair production. Since the electron has no track match requirements in this channel, we do pick up wide angle bremsstrahlung events from $W \to \mu\nu$. We reject these with cuts on the transverse mass $M_T(\mu\gamma\nu)$ consistent with wide angle bremmstrahlung events.

In this combination of triggers and selection cuts, the estimated top selection efficiency is shown as a function of top mass in table I. The $e\mu$ event selection efficiencies have an error of 23% on them which includes systematic and statistical uncertainties.

To arrive at these numbers we have used the ISAJET event generator program [14] and the GEANT based DØ detector simulation program [15].

IV. RESULTS

Figure 1 shows the scatter plot of the missing E_T of the electrons in the effective mass of the electron pair for the ee sample. Figure 2 shows the corresponding distributions for top quark decays of mass 140 GeV/c^2 ($\int Ldt = 2.7fm^{-1}$) . It can be seen that if top quark decays are present, a substantial fraction of these should populate the region with missing E_T's greater than 20 GeV . The concentration of events in the data for ee effective masses between 70 GeV/c^2 and 100 GeV/c^2 is due to the Z boson. After the cuts described in section II, we have no candidates events left.

Figure 3 shows a scatter plot of the p_T of the muon vs E_T of the electron in the $e\mu$ sample for data. Figure 4 shows the corresponding plot for 120 GeV/c^2 top decays ($\int Ldt = 1.2fm^{-1}$). It can be seen that a substantial portion of the top decays will survive the cuts on the muon and electron transverse momenta. After all the cuts described in section III are imposed on the data, one event remains of which more will be said later.

V. ESTIMATION OF BACKGROUNDS AND THE TOP LIMIT

In order to estimate the backgrounds that survive the above cuts, we have generated $Z \to \tau\tau, Z \to b\bar{b}, W + Jets, WW, WZ$ and radiative $W(Z) \to \mu + X$. Additionally we have tried to estimate instrumental backgrounds due to misidentification of electrons, mismeasurements leading to fake missing E_T, muons from π/K decays in flights and cosmic ray muons. Instrumental backgrounds were estimated using data as well as Monte Carlo events. For an integrated luminosity of $7.3 pb^{-1}$, we estimate a total of 0.23 background events above the cuts from all the sources listed in the ee channel. For an integrated luminosity of $7.5 pb^{-1}$, we estimate a total of 0.65 background events above the cuts from all the sources listed in the $e\mu$ channel.

Figure 5 shows the 95% upper limit estimate of the $t\bar{t}$ cross section using the ee and $e\mu$ analyses combined, including the one event observed. The two curves shown are for the two cases where background is subtracted and no background is subtracted from the total expected number of events. We note that zero background subtraction leads to a more conservative limit. Using the cross sections quoted in Berends et al [10] we set a lower limit at 95% confidence limit of 103 GeV/c^2 for the background subtracted case and 99 GeV/c^2 for the zero background subtracted case for the top mass.

VI. THE REMAINING $e\mu$ EVENT

The single event (Run 58796 event 417) in the $e\mu$ plot that is well above the cuts merits further discussion. While we make no claim that we have observed production of the top quark or indeed any other new phenomenon, it is interesting to hypothesize that this event is due to $t\bar{t}$ production and decay to $e\mu$. Figure 6 shows the r-z view of the event, where r is the transverse direction and z the direction along the beam. The electron quality is excellent ($\chi^2 = 51$)and further confirmation is obtained from the information in the Transition Radiation Detector (TRD) . Figure 7 shows the transverse view of the same event.

The muon momentum in the event is measured reasonably well $p_T(\mu) = 110^{+\infty}_{-50}\, GeV/c$.

The muon is missing hits in the first layer of the muon chambers, indicating that it probably transited between two chambers in that layer. The muon track is found in the two muon chamber layers after the toroid and is confirmed by minimum ionizing energy deposition in the calorimeter and a central detector track when extrapolated to the vertex. The error on the muon momentum is approximately Gaussian in $1/p$ and $p_T(\mu)$ is 5σ above the 15 GeV/c event selection cut imposed on it. The missing E_T value is $74^{+\infty}_{-7}$ GeV. It is somewhat correlated with the muon momentum. It value cannot be smaller than 67 GeV for any muon momentum. It can be seen that the missing E_T vector is at almost right angles to the muon and is not influenced greatly by the muon resolution. Both the muon and the electron are well isolated. The event has three jets with $E_T^{\prime s}$ of (30 ± 5) GeV, $(28 \pm 5\,GeV)$ and $(14 \pm 2)\,GeV$. The backgrounds considered above are unlikely to produce this event.

Under the hypothesis that the highest E_T jets from this event are due to the $b\bar{b}$ produced in $t\bar{t}$ decays , we have attempted to extract information on the mass of the top quark using extensions of techniques similar to those proposed by Dalitz et al ([16]). We find that the top mass cannot be lower than 130 GeV/c^2 at 95% C.L. The upper limit is still being studied rigorously but is unlikely to be much higher than 170 GeV/c^2.

To conclude, we obtain a lower limit for the top quark of 103 GeV/c^2 at the 95% confidence level from the ee and the $e\mu$ channels. We have observed one event in the $e\mu$ channel, which is not consistent with the known backgrounds.

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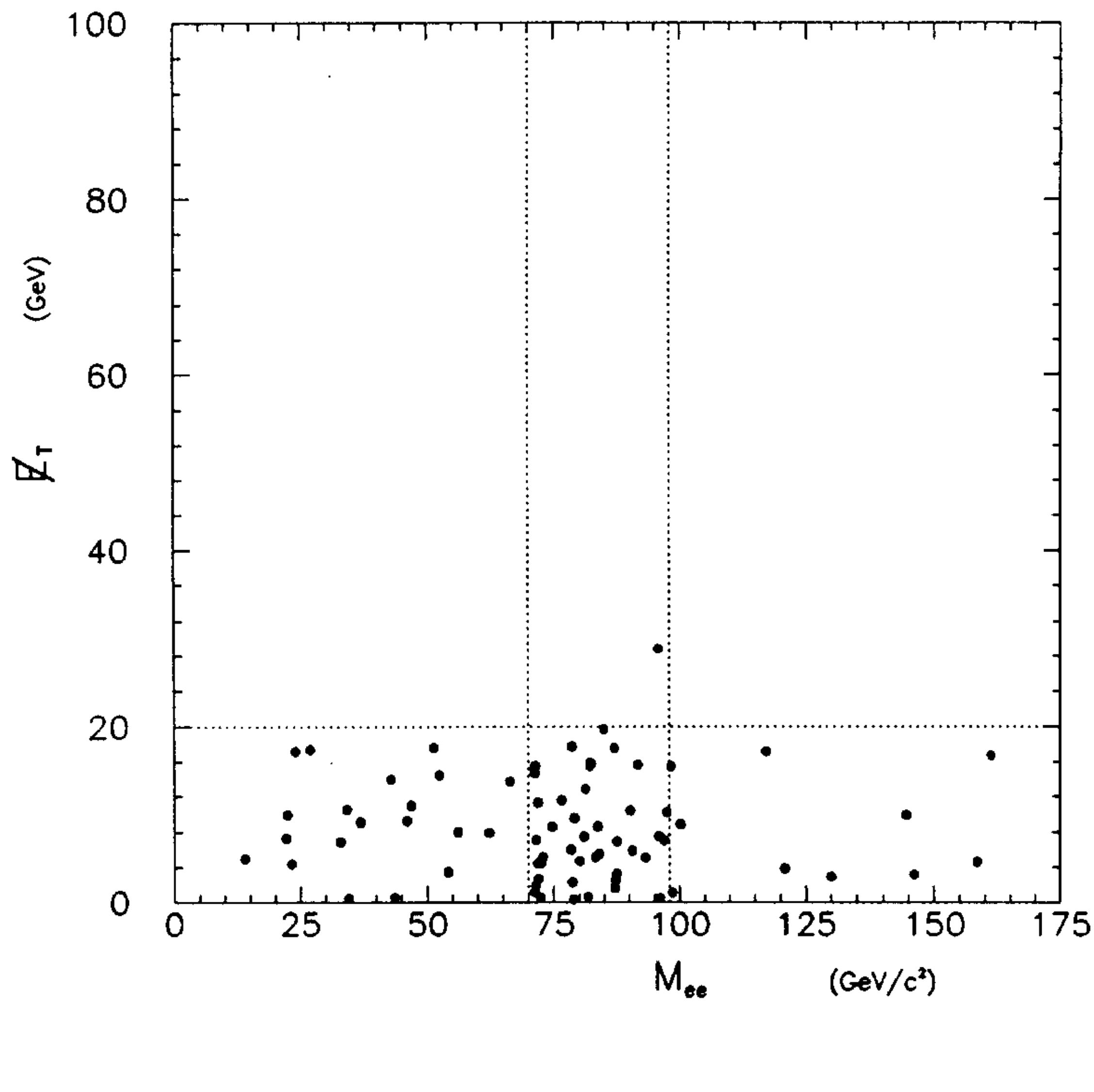

FIG. 1. Missing E_T vs. mass of the ee pair for DØdata.

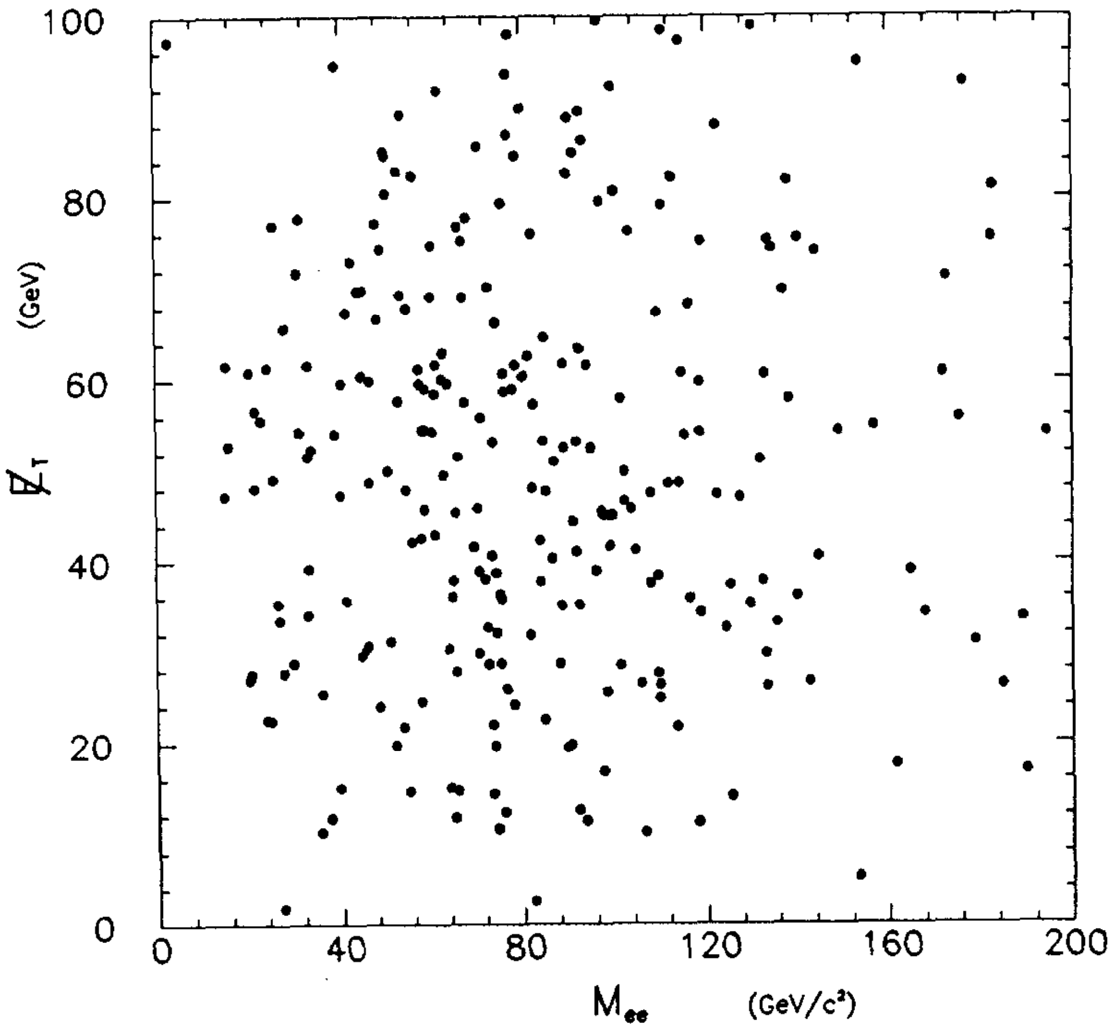

FIG. 2. (Missing E_T vs. mass of the ee pair for $t\bar{t} \rightarrow ee$ Monte Carlo for $m_t = 140\ GeV/c^2$

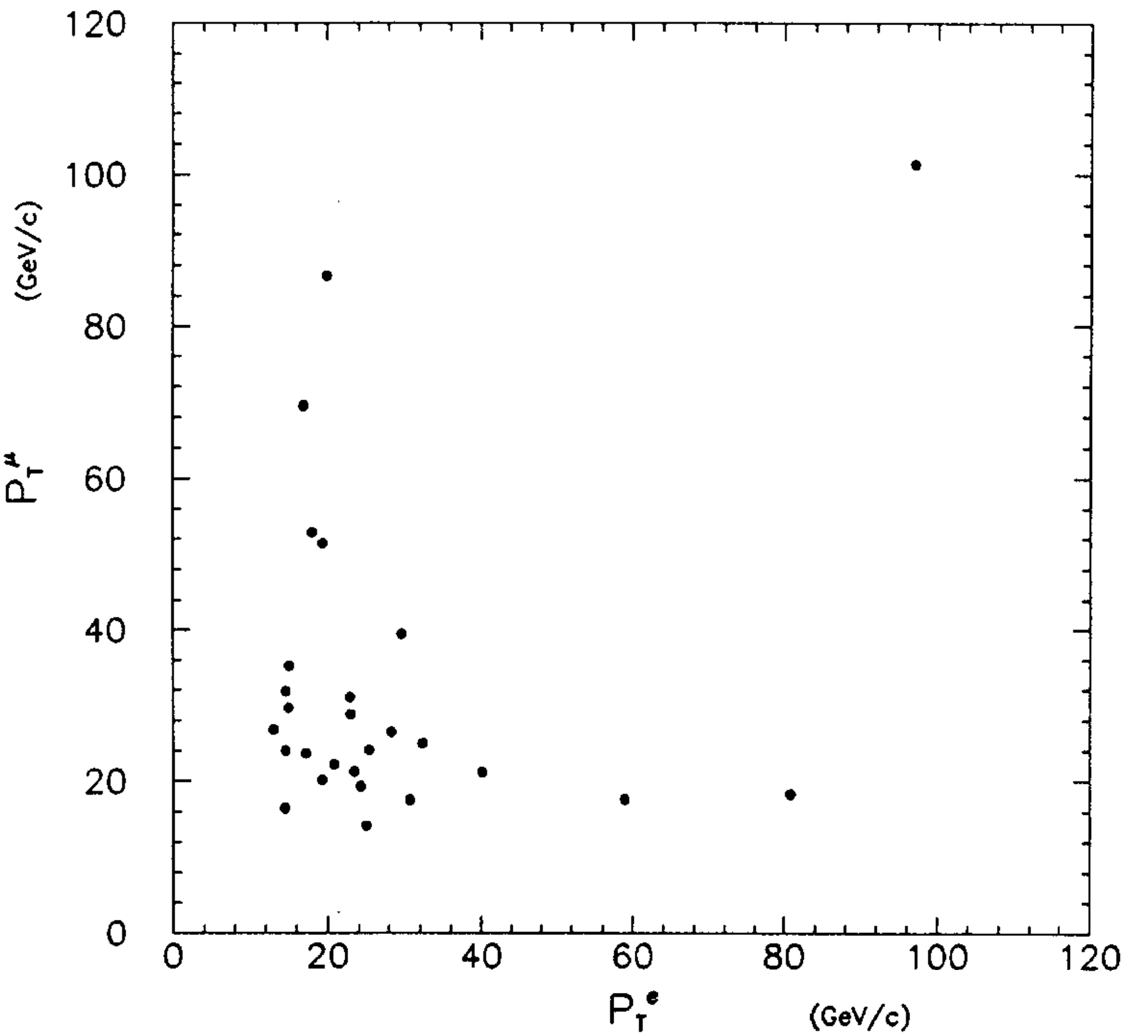

FIG. 3. p_T of muon vs E_T(e) for DØ data

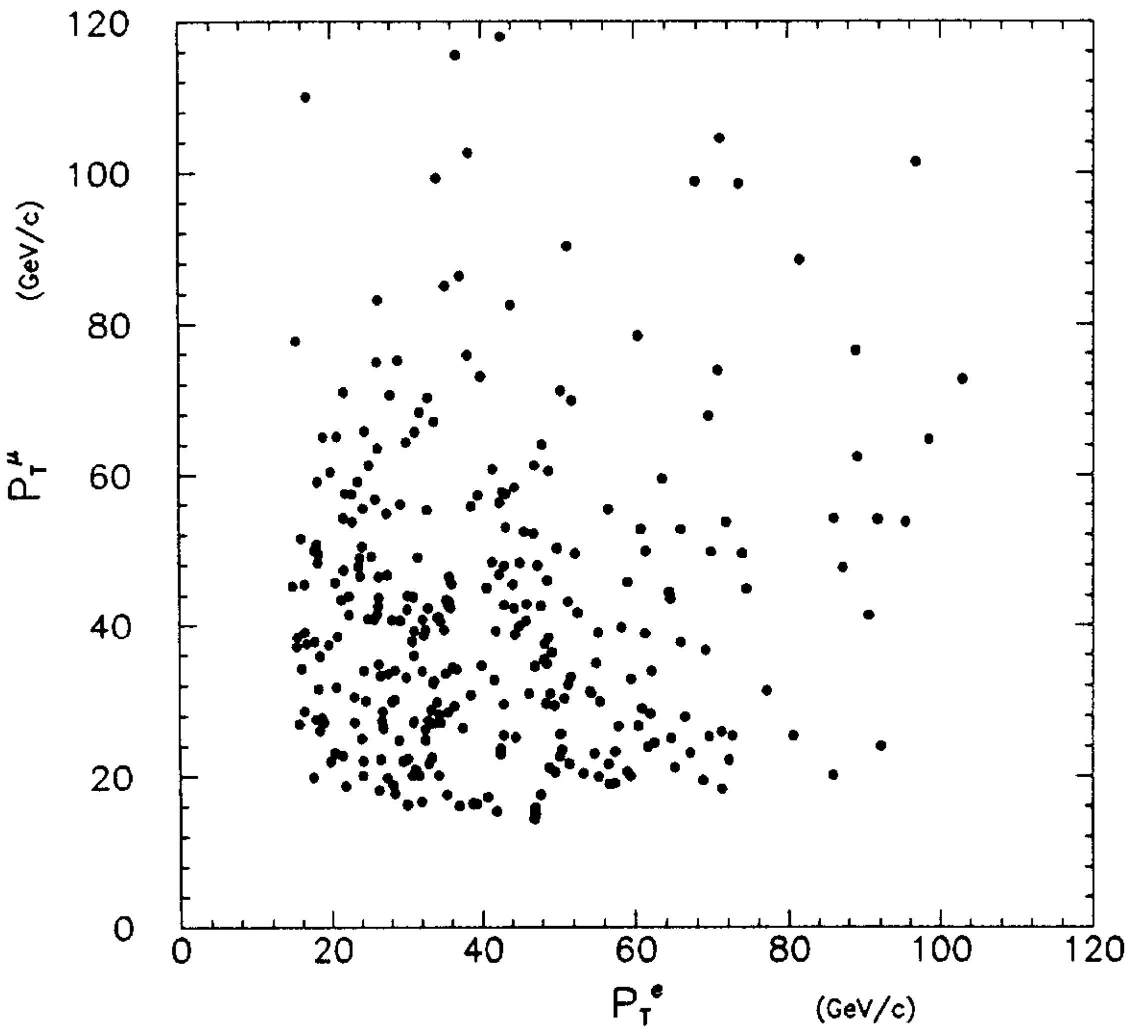

FIG. 4. p_T of muon vs E_T(e) for $t\bar{t} \to e\mu$ Monte Carlo for $m_t = 120\,GeV/c^2$

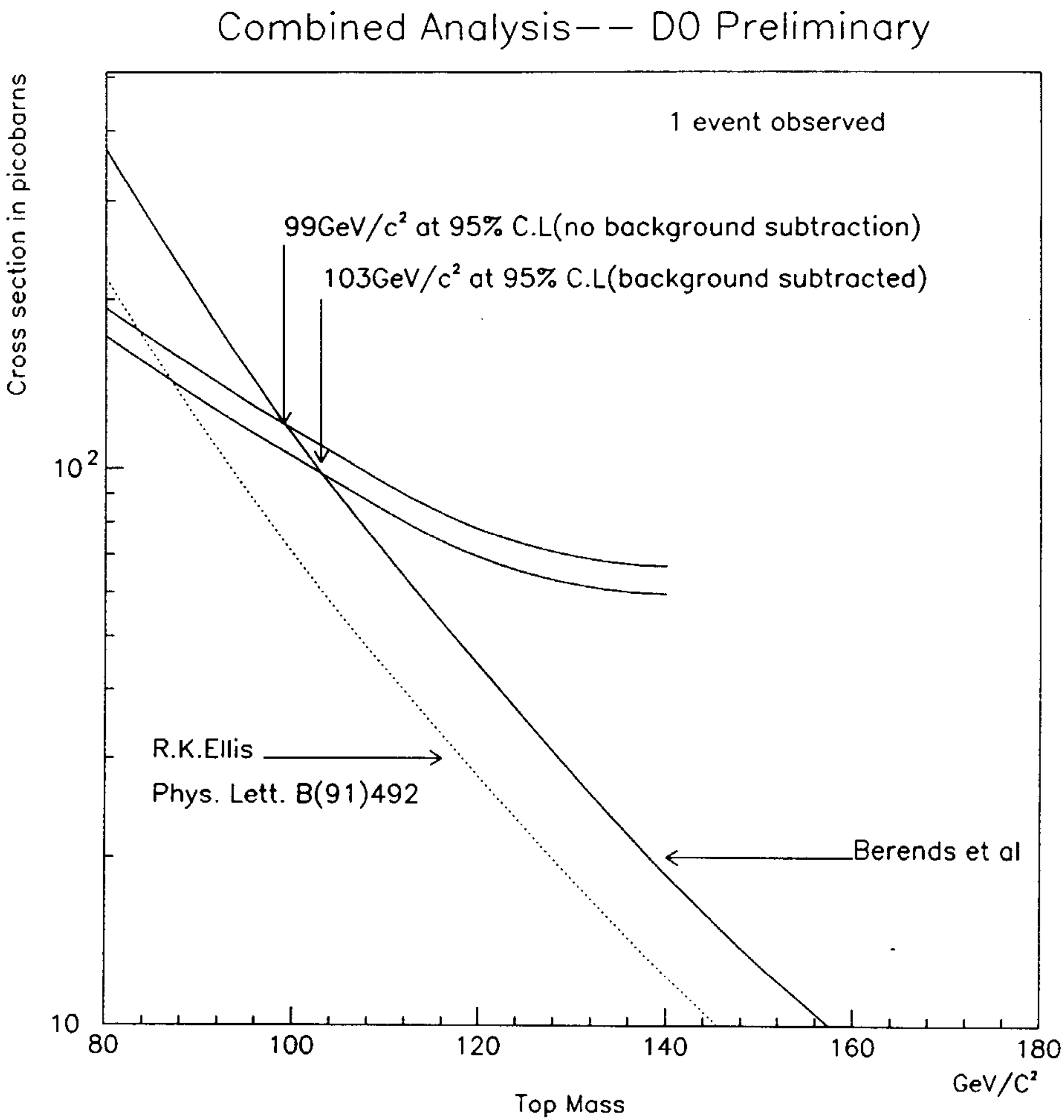

FIG. 5. Cross section for $t\bar{t}$ production as a function of top mass . First curve shows our 95% upper limit deduced from ee and $e\mu$ analysis combined with zero background assumed. The second curve shows our bakground subtracted result.

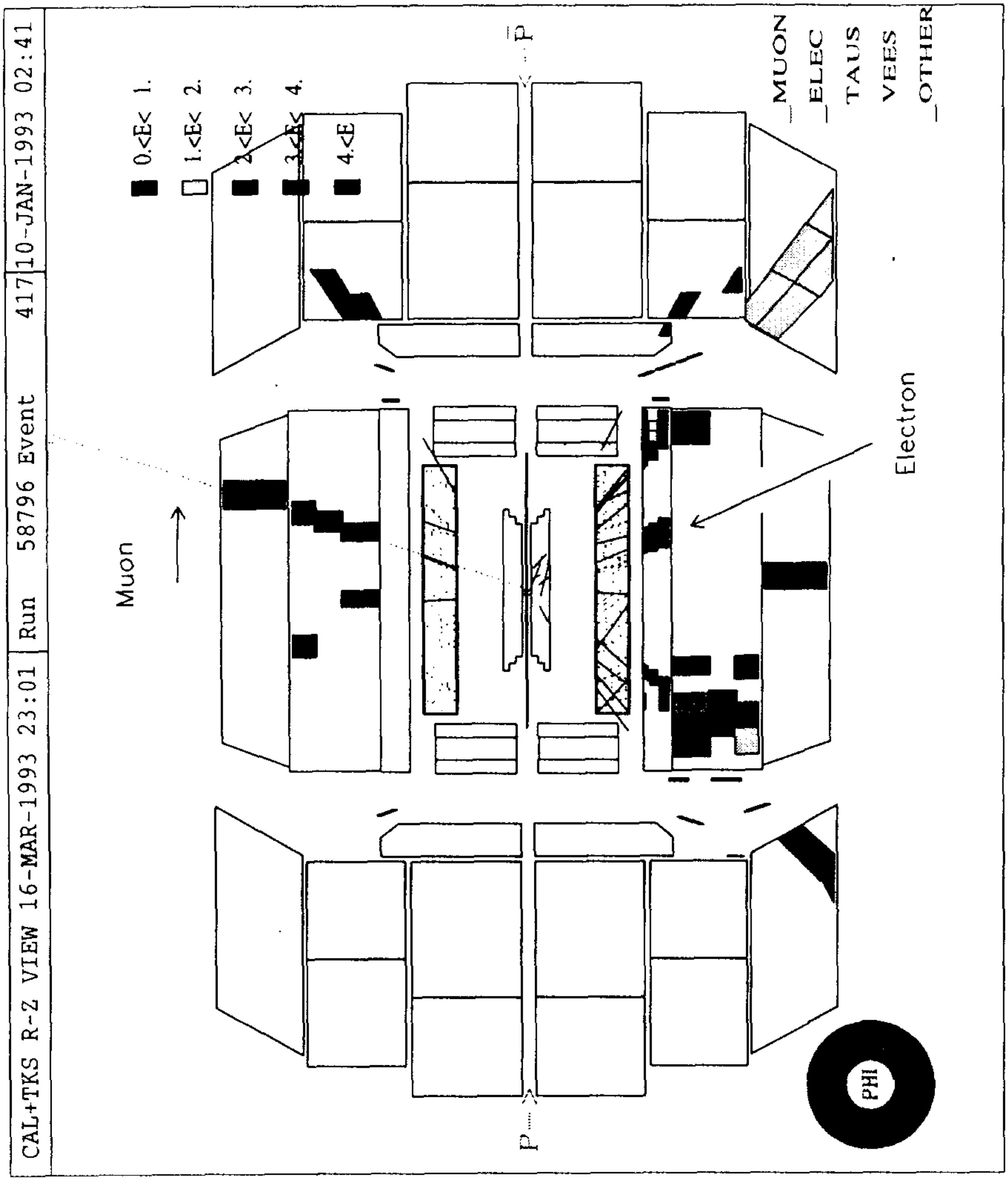

FIG. 6. The longitudinal view of Event 58796/417. Calorimeter cells with $E_T > 1 GeV$ are shown. All phi information is shown. The muon, electron and the jets are clearly seen.

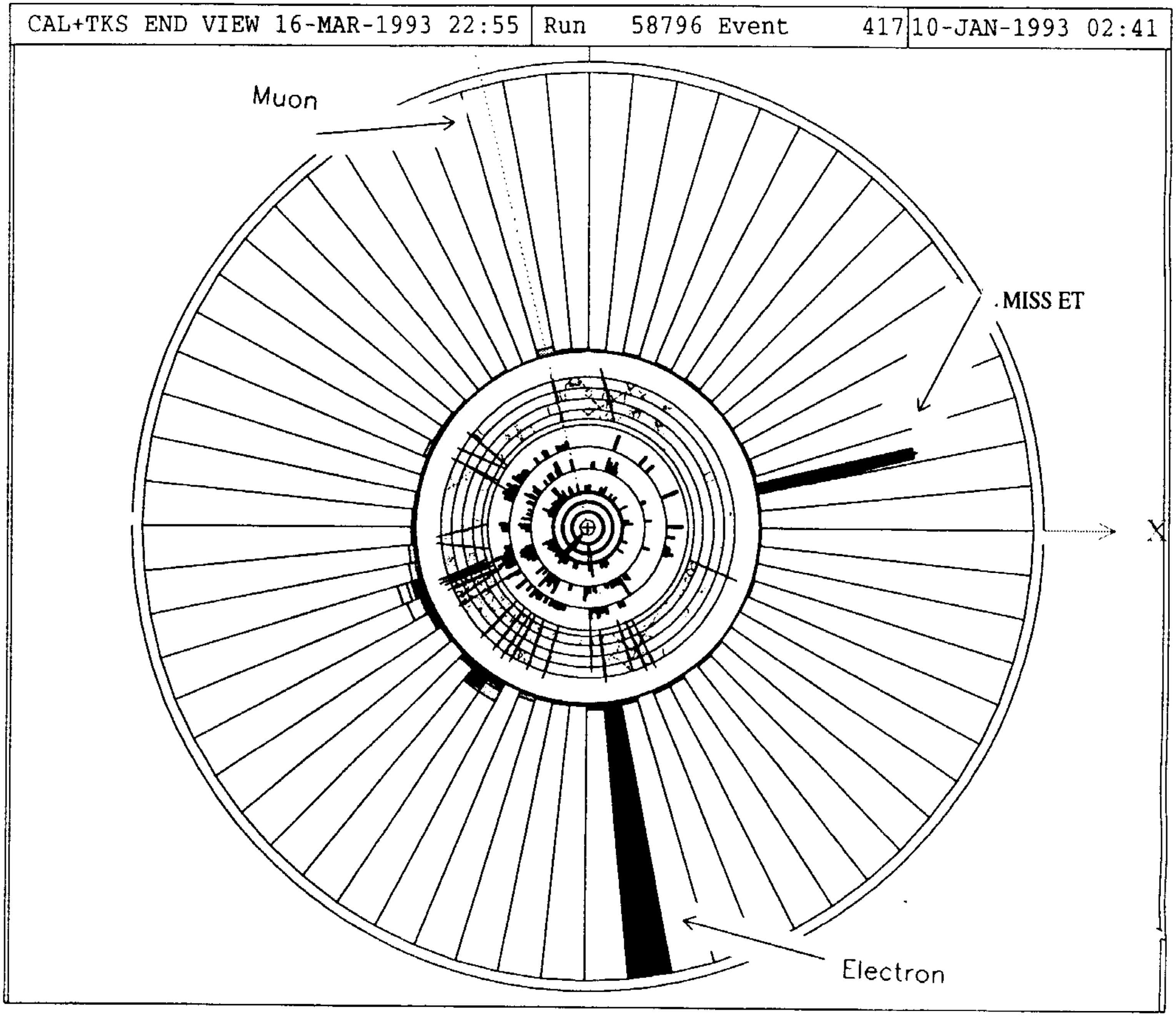

FIG. 7. The transverse view of Event 58796/417

TABLES

TABLE I. Efficiencies and expected yields for ee and $e\mu$ channels as a function of top mass

m_t GeV/c^2	$\sigma \cdot B_{ee}$ pb	Efficiency ee %	$< N >_{ee}$ events	$\sigma \cdot B_{e\mu}$ pb	Efficiency $e\mu$ %	$< N >_{e\mu}$ events
$80\,GeV$	4.6	11.0	3.7	9.1	9.0	6.1
$100\,GeV$	1.3	18.0	1.7	2.5	15.0	2.8
$120\,GeV$	0.5	28.0	1.0	1.0	22.0	1.7
$140\,GeV$	0.2	32.0	0.5	0.5	26.0	1.0
	$\mathcal{L} = 7.3 \pm 0.88\,pb^{-1}$			$\mathcal{L} = 7.5 \pm 0.9\,pb^{-1}$		