Calorimeter TDCs for Run II and beyond

Vaia Papadimitriou

Version 1

September 15, 1993

The purpose of this note is to investigate the neccessity of TDCs for the electromagnetic and hadronic calorimeters for Run II (400 ns cycle) and beyond (132 ns cycle), based on the experience we had with the CHA/WHA TDCs till now.

Contents

1 I. Calorimeter TDCs in CDF

The CDF detector has been described in detail in Ref. [1]. In this note we will point out only a few characteristics of the detector that are relevant to our discussion. The only CDF calorimeters that are equipped with TDCs are the central hadron (CHA) and endwall hadron (WHA) calorimeters. The CHA contains projective towers each subtending 0.1 in pseudorapidity and 15^0 in azimuth. For each CHA tower the light from 32 layers of scintillator is collected by wavelength shifter strips and is brought by light guides to two phototubes located on opposite sides in azimuth. Signals from the last dynode stage of the two phototubes are first amplified and summed together. Then the resulting pulse is discriminated (1 mV threshold) and converted to a voltage proportional to the time elapsed between the discriminator firing and a common stop signal using a custom designed TDC circuit. The WHA signal is timed in a similar way. The TDCs are 16-bit and their full scale range is 3.2 μsec. The response is linear, the intrinsic timing jitter is approximately 200 ps and the temperature coefficients are typically 100 ps/°C.

The Hadron TDCs (HTDCs) which enabled us to determine relative arrival times in the calorimeter with a resolution of $\sim$ 1.6 ns, have been used in several analyses either to provide timing information for the signal or to remove backgrounds which cause out of time hits like cosmic rays, main ring splashes, beam gas, and single phototube discharges.

2 II. TDC timing cuts

The hadron TDC filter routine, HATFLT [2], reduces the cosmic ray background by removing events that have more than 8 GeV of energy in the central hadron calorimeters outside of a time window which is currently $-20<\Delta t< 35$ ns for CHA and $-25<\Delta t< 55$ ns for WHA. These windows were $-10<\Delta t< 25$ ns and $-10<\Delta t< 55$ respectively for the 1987 run [3]. They were broadened during the 1988-89 run because of the T_0 shifts observed during the run. These are quite broad in-time windows if we take into account that the TDC resolution is $\sim$ 1 ns. In Fig. 1 [4] we see the time response of the central calorimeter plotted vs the energy for jet events. This curve includes many TDC channels but the distribution looks similarly broad even for a single channel. Time slewing and t_0 effects have been taken properly into account. The resolution becomes noticeably worse at low energies and the assumption is that this is due to the calorimeter response especially to slow neutrons. One does not see a similar broadening for low energy laser pulses or for muons. The assumption here is that sometimes we have many slow neutrons in the shower, many of them at the TDC threshold or below, and there is not enough in time energy to fire the TDC discriminator. The same effect of slow tails has been seen at the test beam [5], which confirms that this effect is not due to some noise in B0 events but it is a feature of the response of the calorimeters even to a pion beam.

3 III. How we reject cosmic ray backgrounds

Till now the QCD and exotic analyses are using as tools to reject cosmic rays the timing information from the HTDCs, the missing E_t ($\not{E}_t$) significance, $\sigma_{\not{E}_t}$, the electromagnetic energy fraction of a cluster, EMF, the charged fraction, CHF, and the CES/CEM ratio, $R_{CES/CEM}$.

$\sigma_{\not{E}_t}$ is defined as $\not{E}_t / \sqrt{\sum E_t}$. In Fig. 2 (provided by S. Kuhlmann) we see the very big rejection power of the $\sigma_{\not{E}_t}$ cut against cosmics in the prompt photon analysis from the 1992-93 data. These photons come from the 70 GeV trigger. We see that the cosmic rays dominate the high P_T part of the spectrum. This can be also seen in Fig. 3 which shows the fraction of cosmic ray events discarted with various cuts vs E_t. Fig. 3 corresponds to the 1988-89 data. In Run I and in Run II and beyond we will suffer more from cosmics at high E_t because we now have more statistics to explore the high E_t region. The $\sigma_{\not{E}_t}$ cut is certainly very helpful in reducing backgrounds but it is a physics cut and although it is used in the prompt photon, jets, $\sum E_t$ analyses it can certainly not be used in $\not{E}_t$ analyses.

CHF is the ratio of the scalar sum of the transverse momenta of the CTC tracks associated with the leading cluster divided by the transverse energy of the leading cluster. The charged fraction cut cannot be applied in photon analyses and it looses its power even for jets when we come at the plug since we have no good tracking there.

The $R_{CES/CEM}$ and EMF cuts are especially helpful for rejection of cosmics that deposit energy in the EM calorimeters. Although these cuts are not physics cuts, one has to be able to understand their efficiency. In the previous runs, when our statistical errors were large, it did not really matter very much how well we understand these efficiencies. With the current statistics and with the ones from Run II and beyond it will be important for the QCD analyses to understand the systematics better (a few % level).

In Fig. 4, 5 and 6 [6] we show the correlation between EMF, CHF and $\sigma_{\not{E}_t}$ in "jet candidate" events from the quark compositness analysis (HATFLT had already run at the production level). These figures show that the cosmic rays and other backgrounds form isolated islands and therefore can be removed from the sample. Although these plots show that we can remove a big fraction of the cosmics, it requires lots of effort to reduce the backgrounds. We have learned by now how to handle these backgrounds but they may become a limitation in our systematic errors for photon analyses in the future if we do not have additional timing information from the EM calorimeter.

4 IV. Analyses using HTDCs/Prospects

1) In order to reduce backgrounds that cause out of time hits, HATFLT has run in production for the Run IA data for the $\not{E}_t$ triggers and it is part of the "offline cleanup" for all the jet analyses. It was used in particular in the SUSY search [7, 8], in Jet fragmentation studies [9], in the monojet analysis [10] and so on. From studies done with the 1987 data it was found that HATFLT had almost 100% efficiency and it removed 90% of the cosmic ray backgrounds in the central calorimetry, missing 5% due to in time cosmic rays and another 5% due to cosmic rays with EM energy only [3]. The 5% due to intime cosmic rays was consistent with the ratio of HATFLT in-time window over the 700 ns wide TDC window (at the time one was not looking at the first 150 ns of the ADC gate before the enabling of the TDC). With Run IA conditions the in-time cosmic ray fraction is more like 6.5%.

2)Heavy Stable Charged Particle Search

The timing information from the HTDCs has been used effectively to distinguish between fast and slow particles in the heavy stable charged particle search. A number of theories beyond the Standard Model like compositness, superstrings, technicolor, monopoles, heavy leptons and quarks belonging to

Representation	5 pb^{-1}	20 pb^{-1}	100pb^{-1}
<u>3</u>	190 GeV	240 GeV	305 GeV
<u>6</u>	285 GeV	345 GeV	410 GeV
<u>8</u>	290 GeV	350 GeV	415 GeV
<u>10</u>	360 GeV	410 GeV	480 GeV
Stable Leptons	-	-	85 GeV

Table 1: Lower Mass Limits Attainable for Various Classes of Stable Particles as a Function of Total Integral Luminosity

higher color representations allow the existence of new massive stable particles. In CDF we have searched for heavy stable charged particles [11] by using 3.5 pb^{-1} of the 1988-89 data. In Fig. 7, taken from the same Reference, we show the calorimeter time difference between pairs of tracks from a sample of $p\bar{p}$ interactions and for a sample of cosmic rays. This difference had a mean value of 20 ns for cosmic rays and 0 ns for dimuon tracks from $p\bar{p}$ interactions. Finally, the hadron calorimeter time was required to be at least 5.4 ns late compared to $\beta = 1$ particles. In Fig. 8 we show the hadron calorimeter time relative to $\beta = 1$ particles vs energy deposition for the data sample. It is probably fair to say that it would be much more difficult to do this analysis without the HTDCs. The only other possibility to find timing information for charged particles is to use CTC timing for the tracks. One of the problems in this approach would be the fact that the sample is selected on the basis of one track (high P_T muon) and therefore it would be biased. Another problem would be that the thickness of the CTC is smaller than the thickness of the CHA. Therefore one can distinguish better between fast and slow particles by using the calorimeter. Although, as far as I know, nobody is working currently on this analysis we can certainly improve our present mass limits by taking profit of the increase in the statistics from Run I and Run II. As seen in Table 1 taken from Ref. [12], the lower mass limits for various classes of stable particles could be improved by factors of 1.3-1.6 if we compare the limits between 5 and 100 pb^{-1}. The different rows correspond to different color representations.

5 V. Analyses that need/would improve with EM TDCs

The analyses that basically need EM TDC information are the ones that have to deal with photon plus $\not{E}_t$ signatures.

Unstable photino search

If the photino, $\tilde{\gamma}$, is the lightest SUSY particle (LSP) then it is stable and it behaves like a neutrino, that is, it does not deposit any energy in the detector. There are models though in which the LSP is the higgsino, $\tilde{H}_0$, and the photino decays to $f\bar{f}\tilde{H}_0$ and $\gamma\tilde{H}_0$. We can assume that the radiative mode $\gamma\tilde{H}_0$ is dominant when the mass of the photino is not fairly heavy or if $m_{\tilde{\gamma}} \leq m_{\tilde{f}}$ (see Ref. [13]). In this case one searches for γ's in time coincidence with the $\not{E}_t$ event and it would be helpful to have timing information from the EM calorimeters. The cosmic ray problem can be more or less severe depending on the model we assume. Since supersymmetric particles are generally admitted to be produced in pairs, we could produce pairs of photinos or squarks or gluinos and so on. If we produce mostly photino-photino, then the final state would have a two photon plus $\not{E}_t$ signature. If we produce mostly squark-squark or gluino-gluino then the photino is a product of the decay chain and depending on the expected branching ratios we may have one or two photons in the final state plus $\not{E}_t$ plus jets. Although it would help us to have jets in the final state in order to reduce cosmic ray backgrounds, the problem will not be trivial.

Excited neutrino

One can check compositness models for quarks and leptons by looking for excited neutrinos. These neutrinos could be produced either singly via $q\bar{q}\to\nu\bar{\nu}^*$, $\nu^*\bar{\nu}$ or pairwise via $q\bar{q}\to\nu^*\bar{\nu}^*$. One decay possibility for an excited neutrino would be: $\nu^*\to\gamma\nu$. Since the photon couples only to charged objects, one would have to introduce a charged loop coupling. The same excited neutrino could also decay as $\nu^*\to Z\nu$ (tree diagram) where the Z goes to leptons. That would be a more copious decay and easier to detect. Also if one wants to check compositness models one does not have to check them neccessarily through excited neutrinos. They could be checked with excited electrons or quarks which are easier to detect.

Higgs search

Another possibility would be to look for Standard Model Higgs produced in association with W or Z. LEPI has already set a limit of $m_H \geq\sim 60\ GeV/c^2$ [14] and LEPII can probably reach limits of $m_H \geq 80 GeV/c^2$ [15]. A Higgs production mechanism at the Tevatron that leads to photon + $\not{E}_t$ signature could be $q\bar{q} \rightarrow$ Z* $\rightarrow$ Z H^0 $\rightarrow \nu\bar{\nu}\gamma\gamma$. Again one would have to assume some charged loop coupling between the H^0 and the photons and therefore the branching ratio of H^0 $\rightarrow \gamma\gamma$ is at the order of 10^{-3} while the corresponding ratio to $b\bar{b}$ is on the order of 90%.

If though it turns out that the Higgs ("bosonic Higgs") couples much more strongly to dibosons (WW, ZZ, $\gamma\gamma$) than it does to fermions ($f\bar{f}$) and if $m_H \leq 2m_W$ then the diphoton signature would be the dominant signature for H^0 discovery [16, 17, 18]. In Fig. 9 [19] we show the branching ratios of a bosonic Higgs as a function of its mass. In this case the coupling of Higgs to diphoton occurs through a W-boson loop. The Higgs again is produced in association with W or Z and one can consider both the leptonic and hadronic decays of the W and Z bosons. It looks like that with 100 pb^{-1} we should be able to search for a Higgs up to 100 GeV before the comissioning of LEPII [19]. Although Ref. 19 has assumed 100% efficiency for detection of a photon and has not considered backgrounds from cosmic rays, it seems we would not have a problem with this search if we look for two photons and two jets. We would certainly have considerable problem with cosmics though, if we were looking in the inclusive photon spectrum trying to find a change in it due to the new physics. Since Run II is supposed to start only at the end of 1996 and since LEPII is scheduled to start in 1995, we would have to do this search without EM TDCs anyway if we want to have a result before LEPII. TDCs are not necessary in this case but they would be helpful. In case such a "bosonic Higgs" exists, one could argue that it would help to have EM TDCs because it would be interesting to confirm it even if LEPII has seen it before us.

One might also consider searching for a "semi-bosonic Higgs", that is a Higgs which is associated with the generation of the weak-vector-boson masses and the top quark but not with any other fermion (this is because the top is much heavier than any other fermion). The dominant decay of such a Higgs is to two gluons via a top-quark loop for m_H = 60-80 GeV but it still has a significant branching ratio to two photons. More than 1000 pb^{-1} of integrated luminosity would be neccessary to establish a signal [19].

In all the above cases it would be easier for the trigger to look for a Z decaying to e^+e^- or $\mu^+\mu^-$ instead of a Z decaying to $\nu\bar{\nu}$. Our statistics though can be increased if we look for this additional channel.

Heavy stable neutral particle search

This search is going to suffer from lots of cosmic ray background. In the charged particle search, since we have a track we know in which calorimeter tower it projects and we know in which tower to look for in-time or late hits. For neutral particles (if they interact et all with matter) we do not have this information and we have to look at all the TDC hits in all the towers. In that case EM TDCs would be of great help since one could use them to look for two late TDCs in coincidence.

Heavy stable charged particle search

The Heavy stable charged particle search would certainly benefit from EM TDCs as well since the dominant systematic for that search was the big thickness (depth) of the hadron calorimeter [11]. The CEM calorimeter has a much smaller thickness.

Magnetic monopole searches

The monopoles we are talking about here are the ones proposed by Dirac to account for the quantization of electric charge. If magnetic charge is a conserved quantity, monopoles are pair produced. Ref. [12] gives some properties of a magnetic monopole to consider for detection. Among its striking features are a very large energy deposition of energy in the EM calorimeter and an acceleration in the direction of the magnetic field. In the CDF detector all but the highest p_T monopoles will move to the forward direction. In this case TDCs in the EM (PEMU as well) will help in the detection.

Monojet analysis

In the monojet analysis [10], cosmic rays are removed by requiring that the charged fraction of the leading cluster is greater than 0.1. Events with charged fraction less than 0.2 and out of time energy in the HTDCs greater than 0.4 GeV were also removed. Some additional rejection was gained by removing from the sample events with CES/CEM ratio less than 0.2 and charged fraction less than 0.2. After all the cosmic ray related cuts, 19 cosmic ray and beam gas events have been removed from the sample and the residual background that was due to cosmics was 9 events. These events have a big fraction of energy deposited at the EM calorimeter and they could be reduced with information from EM TDCs. On the other hand one could remove this residual background (see Fig. 10) without a big loss in efficiency if one was requiring that the charged fraction is bigger than 0.2.

SUSY

The cosmic ray background is reduced in the SUSY analysis by HTDC information, by a CHF cut and by hand scanning. The charged fraction cuts currently applied in SUSY searches reduce the signals by $\sim 10\%$. Therefore it would help to have an additional handle with EM TDCs, although our mass limits will not be improved very much with an only 10% increase in the acceptance.

EW studies

With EM TDCs one could make the tracking efficiency studies which are necessary for the W mass measurement easier. The way one proceeds in these studies is to collect the W events without tracking requirements and then look for the track. The tracking efficiency can be also studied using Z decays though. In the previous runs we did not have enough Z's to do this study but in Run II and beyond we could use Z's to do it with quite good precision. Having EM TDCs would also help in searches of W' or Z' where we are looking for stiff electron tracks and would like to be able to make only loose tracking requirements.

Photon analyses

The photon analyses, the prompt photon cross section in particular, may also benefit from EM TDCs by reducing their systematics related with the cuts that reject cosmic rays and other out of time backgrounds. Currently the systematics are in the order of 12%-20% and they are expected to be reduced to approximately 5% for $P_T > 50$ GeV/c by the time we will be publishing the Run IA photon analysis. The 5% error is the one we should focus on because this high P_T region is the one dominated by cosmic rays. This 5% error will be dominated by uncertainties in the π^o calibration and in the knowledge of the exact amount of material in the solenoid. The systematic error in the photon cross section due to cosmic rays is in the order of 1-2%. This error is due to not knowing how many cosmic rays are left in the sample after the cuts and how many prompt photons have been removed due to the cuts. In this case the cosmic rays are removed with the $\not{E}_t$ cut, which is checked against an $R_{CES/CEM}$ cut. Since the background fraction of cosmics with EM energy only will not become significantly worse from Run IA in Run II and beyond (see section VI), we cannot make a strong argument in favor of EM TDCs from the prompt photon cross section analysis alone.

6 VI. Collider/CDF running conditions

In the Tevatron operation till now, including Run I, the proton-antiproton bunch crossings were 3500 ns apart. We will refer to this whole period as Run I from now on. For Run II we expect that the bunch crossings will be 400 ns apart, and for the Main Injector era (Run III) we expect beam crossings every 132 ns. The CDF ADC gate was 850 ns wide for Run I, covering the window from -200 ns to +650 ns around the beam crossing. Due to noise problems [20, 21], the Hadron Calorimeter TDCs for CHA and WHA were enabled $\sim$ 150 ns after the calorimetry became active. The results of some studies performed by S. Kuhlmann showed that the noise went through the anode and through the PMT base to the TDC. As it turns out by looking at the characteristics of the calorimeter pulses (see Fig. 11) the ADC gate cannot be shorter than $\sim$ 100 ns in the future. For Run II and Run III we expect that the ADC gate will be 400 ns and 132 ns wide respectively [22] and we plan to have the TDCs active during the whole time period that the ADCs are active.

The probability for a cosmic ray to enter in the ADC and TDC gates and contaminate an event within a cycle, is the ratio of the ADC gate width over the duration of the cycle times the ratio of the in-time TDC window over the width of the ADC gate. Therefore this probability was $(850ns/3500ns) * (55ns/850ns) = 0.016$ in Run I, and it is going to be $(400ns/400ns) * (55ns/400ns) = 0.14$ in Run II and $(132ns/132ns) * (55ns/132ns) = 0.42$ in Run III if the TDC in-time window does not become narrower [23]. In this case, the only way for the background fraction due to cosmics to stay as it was in Run I would be to increase the luminosity by a factor of 9 in Run II and by a factor of 26 in Run III compared with Run I. Since we beleive though that from now on we will be able to control the T_0 within 1-2 ns, we hope that we could go back to the original HATFLT in-time window which was 35 ns wide. In that case we would have to have an increase of luminosity by a factor of 5.5 in Run II and by a factor of 17 in Run III compared with Run I in order to keep the background fraction due to cosmics the same. One could try to narrow the HATFLT window even more by having an energy dependent window. This way it would be conceivable to make the window narrower by a factor of $\sim$2 at energies above $\sim$ 20 GeV (see Fig. 1).

As far the EM calorimeters are concerned, since we currently have no TDCs on them, the probability for a cosmic ray that deposits energy only at the EM calorimeter to contaminate an event within a cycle is 24% in Run I and it will be 100% in Run II and Run III (it could be only 33% in Run II if we follow a different scheme described below). So there is an increase of a factor of 4 (in the worst case) and we would like to have a corresponding increase in the luminosity in order to keep the fraction of the EM cosmic background the same.

The peak luminosity in Run IA was 9.2×10^{30} [24] and we expect that we will have luminosities as high as 3×10^{31} in Run II and 2×10^{32} in Run III. Although the above maximum peak luminosity in Run IA does not correspond to the maximum average luminosity in the same run, one could use the above numbers to get a rough figure on the expected increase of luminosity in the future runs. It turns out that we expect an increase of a factor of 3 in Run II and a factor of 22 in Run III. Although the expected Run II factor could be higher (3.5-4.0), it still seems a bit low compared to the one (5.5) we would like to have in order to keep the cosmic background fraction the same in the CHA.

Taking therefore into account the fact that the rejection power of the HTDCs will be reduced, we consider the possibility of implementing EM TDCs as an additional handle. The fact that the CEM has a much smaller depth than the CHA and the fact that we will have smaller tails in the EM timing distribution make us hope that we could impose a tight window cut there and regain some of the lost power of the HTDCs. Note that a big fraction of hadronic showers look like minimum ionizing particles in the EM calorimeter.

As far as Run II is concerned, from very recent discussions with C. Nelson I understand that it is not clear yet what would be the width of our ADC gate: it could be either 400 ns or 132 ns, whatever seems more appropriate. As far as cosmics are concerned, I think we would benefit from a 132 ns gate in Run II. If we had such a gate, then the necessary increase in luminosity by a factor of 5.5 that I have mentioned above would be only a factor of 1.8 which is below the the expected increase of a factor of 3. That would make EM TDCs less neccessary as an additional handle due to the loss of rejection power in HTDCs. Of course the physics reasons for which we would like to have EM TDCs would still be there.

If we decide to implement EM TDCs we should investigate one more issue: since for the W mass measurement and other analyses we depend on the good resolution of the CEM calorimeter, we should try to understand how much we will possibly degrade the resolution by the addition of the TDCs. We do not expect any big deterioration but still we have to perform some tests.

7 VII. Calorimeter TDCs and Muon Systems

In Run I the FMU chambers were located ~ 10 m away from the interaction point. For Run II FMU will move closer to the interaction point (~ 5 m away) increasing in this way the polar angle coverage for muons. This will create some triggering problems though; the FMU chambers were built to form roads with the planes of chamber cells which point at a vertex 10 m and not 5 m away. The trigger roads can be rewired to work under the new conditions but at the cost of not having a sharp P_T threshold. The FMU people plan to use scintillator signals from the PHAU/PEMU as a L1 trigger. They might be also able to use their own scintillator signals but probably the occupancy will be too high at Run II and Run III. Till recently they were not planning in using timing information from the plug calorimeters. If there is timing information available though, they can probably use it either at L1 or at higher levels to reduce the trigger rates.

The CMX detectors have used the HTDC information already in Run IA in order to reduce the trigger rates. The addition of a HTDC requirement to CMU reduces the L1 trigger cross section for the inclusive muons by a factor of ~ 2 and for the dileptons by a factor of 2.5-4.5 compared to Run IA conditions [25]. Both CMX and CMU need basically only the latch information from the HTDCs. In Run II and beyond the HTDCs will be used in order to tag the crossing in which the muon chambers fired.

8 VIII. Which calorimeters need TDCs most?

If one would like to put some priority at which calorimeteres need TDC information in Run II and beyond, one could say that CHA/WHA TDCs are the most important. Then come the PHA and CEM TDCs which seem to be equally important among themselves and then we have the PEM TDCs. This is so because as we have already seen the cosmic rays dominate the high P_T region which makes it important for the central calorimeters to be equipped with TDCs. On the other hand since our tracking is not good at the plug and forward regions it becomes difficult to reject cosmics without TDC information in the Plug Upgrade calorimeter. We hope to be able to have a tight in-time window for the PHAU and in this case the PHAU TDCs will do most of the job in reducing the backgrounds in the plug; this has not really been tested during the last test beam though. If we would like to prioritize further between CEM and PHAU and if we are willing to accept that the background fraction of cosmics we had in the central calorimeters in Run IA is satisfactory, then it seems it would be more important to have timing information at PHAU than at CEM.

9 IX. How to build the TDCs

Here we describe three different schemes for implementing TDCs in the calorimeters and we try to address their feasibility.

A. Possible Schemes [26]

a) Two separate cards for the ADCs and TDCs; the ADCs use the anode signal from the phototube and the TDCs use the dynode signal.

b) Same card for the ADCs and the TDCs. Both ADCs and TDCs use the anode signal from the phototube. There are two possible scenaria in this case.

i) The signal for the TDC is a voltage pick off before the integrator and it goes through a buffer to the TDC.

ii) The signal for the TDC gets picked off after the integrator.

Both i) and ii) have advantages and disadvantages. One of the disadvantages of i) is that if in addition to the voltage pick off one also picks off charge from the anode, then one might introduce nonlinearities in the TDC function. Also the buffer involved might introduce noise into the signal before the integration. The disadvantage of ii) is that if one tries to get time information from the integrated pulse, one introduces time slewing which can be avoided only by a filter which will differentiate the integrated pulse and reproduce the original pulse. This differentiation though may enhance the system noise and introduce it in the TDC signal.

c) Two separate cards for the ADCs and the TDCs. Both the ADCs and TDCs use the anode signal from the phototube. The TDC card picks off a voltage from the anode cable as it goes to the integrator.

As far as noise problems are concerned, scheme a) is the safest and scheme b) is the worst. The Particle Instrumentation Group has to do additional work in order to prove that scheme c) is feasible. Schemes a) and c) are most cost effective than sceme b) as far as the staging option is concerned; in scheme b) one would have to build more cards than needed from the very beginning even if the TDCs would be staged. Scheme b has the additional disadvantage that in case we decide to put one TDC channel per trigger tower instead of one channel per physical tower, there might not be enough room on the VME card to fit the additional circuitry needed for an analog summation of the ADC channels of the towers within a trigger tower.

B. Can we use the dynode option?

Plug Upgrade Hadron Calorimeter (PHAU):

The PHAU has 22 layers and the expected number of photoelectrons (pe's) per layer per minimum ionizing particle (mip) is in the range 1.5-2.0 [27]. A muon will leave 33-44 pe's in the calorimeter and with a gain of the PHAU phototubes in the order of 4 x 10^5 we will have $Q_{anode} = 2.1 - 2.8$ pC. Knowing that the PMT anode signal is roughly triangular with 40 ns base [28], the peak voltage at the anode is $V_{anode} = 5 - 7$ mV. According to Ref. [29] the gain at the last dynode is ~ 8 and the mean signal amplitude available from the dynode will be 4.5-6.0 mV.

We need to be able to identify a muon in the plug hadron calorimeter because we want to be able to use this signal for the FMU system. Since the Particle Instrumentation Group (P.I.G.) feels optimistic about providing thresholds as low as 1 mV, we expect to have no problem in identifying a muon at PHAU.

Plug Upgrade Electromagnetic Calorimeter (PEMU):

The PEMU has 23 layers and the expected number of pe's per layer per mip is 1.5 [30]. Taking into account the fact that the gain of the PEMU phototubes is in the order of 5 x 10^5, we will have $Q_{anode} = 0.28$ pC and assuming a triangular pulse with 40 ns base as above, we have peak current of 14 microamps or $V_{anode} = 700$ microvolts on 50 Ohms. According to Ref. [31] the gain at the last dynode is ~ 8 and therefore the mean signal amplitude available from the dynode will be 613 microvolts. It looks that we would have a hard time to identify muons with PEMU with 1 mV thresholds. If the only reason we want the EM TDCs is to reject muon bremsstrahlung then this is not a problem because it would be sufficient to have a threshold corresponding to about 10 GeV. If we want though to use the PEMU TDCs in coincidence with the PHAU TDCs in order to identify out of time showers then we would like to be able to detect a mip at PEMU.

PEMU phototubes can have a higher gain by a factor of 2 at most. This would bring V_{anode} to ~ 1.2 mV which is still low if the threshold is at 1 mV. The increase in gain though implies that the protection circuit of the phototubess has to be rebuilt. This would cost $\sim$ 1 $ per PMT and the PMTs would have to be retested.

Central Electromagnetic Calorimeter (CEM):

Since the phototube bases for the CEM do not have dynodes we will have to change the bases if we follow this scenario. For the CEM calorimeter we have 220 pe/GeV, a mip corresponds to 350 MeV and the CEM phototubes have a gain of 1.2 x 10^5 [32]. This means that a muon will deposit a charge of $Q_{anode} = 1.48$ pC and assuming a triangular pulse of 70 ns base, we have peak current of 42 microamps or $V_{anode} = 2.1$ mV on 50 Ohms. This seems to be more or less OK if we assume a 1 mV threshold. For CEM one should also keep in mind that we could use the x 16 channels if we need higher PMT gain.

Since it would be useful to put TDCs at CEM and since that would require a change of bases if we want to adopt option a) of section IX.A, it makes sense to investigate further the feasibility of option c). P. I. G. has started this investigation and will let us know more in about 2 weeks' time. This investigation which involves understanding the source of the noise mentioned in section VI and reducing it significantly had to be done anyway because we want to have the TDCs and ADCs active for the same amount of time and we cannot afford in Runs II or III having the TDC enabled 150 ns after the ADC.

10 X. TDC per trigger tower vs TDC per physical tower

TDC information at the trigger tower only, is probably adequate for most of our studies. Usually the cosmics leave energy in more than one physical tower and we will be able to detect them. On the other hand, since the TDCs fire on the first particle to strike a particular calorimeter tower, it is possible for a slow particle to be missed because a faster particle in the same tower had already fired the TDC. If we have one TDC per trigger tower instead of one per real tower we will be more sensitive in backgrounds from late cosmic rays (after the interaction). In that case it would be desirable to have a 2-hit TDC. Let's assume that we have a late cosmic ray and that the TDC has fired due to a minimum bias event that came before it. In this case we cannot detect the cosmic ray, so let's ask the question how much more often will this happen when we have one TDC per trigger tower instead of one

TDC per physical tower. From previous CDF measurements [33] we know that $dN_{ch}/d\eta$ is 3.95 ± 0.03(stat)±0.13(syst) at 1800 GeV. This measurement was done using minimum bias events. Since the CHA trigger towers are $\Delta\eta$ x $\Delta\phi = 0.2$ x 15^o big, we have 3% probability for a minimum bias event to fall in a CHA trigger tower. If we try to account for neutral hadrons as well, like kaons and Λ's (π^0's will be seen at the EM calorimeter), and assume that $dN/d\eta$ is 5, then we could say that the HTDCs would fire $\sim$ 4% of the time due to cosmics if we had one TDC per trigger tower. This number would have to be divided by 2 for one TDC per physical tower. For EM trigger towers we expect a similar effect if we take into account the fact that for every two charged pions we have one π^0 produced, that the two photons from the π^0 decay are unresolved (one cluster), that the EM sees the charged particles as well and that we have some small contibution from neutral kaons and Λ's. Anyway, an increase by about 2-3 % in the cosmic ray background due to the fact that we might have TDCs per trigger tower instead of TDCs per physical tower, probably it is not going to hurt us.

11 XI. Specifications

Least Significant bit (LSB) $\leq$ 1 ns

8 bit TDC is enough to cover the 132 ns spacing between beam crossings. In order to cover the 400 ns spacing for Run II we would need a 9 bit TDC unless we are willling to have LSB of 2 ns.

Differential non-linearity $<$ 1 ns.

Integral non-linearity $<$ 0.5 ns.

Temperature stability factor $<$ 100 ps/^{o}C.

Would like to be able to see muon in the CHA/WHA, PHAU, CEM and possibly PEM.

It would be helpful to have 2-hit capability but it is not neccessary. This will become a more important issue if we put one TDC per trigger tower.

More important than having 2-hit capability would be to have the raw TDC readings inependent of the pulse amplitude as much as possible. It would be very desirable if the TDC output was allowed to vary by less than

1 ns in case the input amplitude varies between threshold and 10 times threshold for example. A constant fraction TDC could be a solution for this. The TDCs will have to be custom made and it is not very straight forward to build a constant fraction TDC. According to C. Nelson, Le Croy has stopped selling constant fraction TDCs because they had problems with them.

We would like that the TDCs and ADCs are sensitive during the same time. We would like to enable the TDCs at the same time we enable the ADCs provided they start being both active at the same time. If we need to have the TDC enabled after the ADC in order to avoid the noise due to the ADC gate, this time difference should not be bigger than 10 ns for Run III conditions.

Multithreshold capability would be desirable but it is not neccessary.

One could also consider the possibility of substituting the TDCs with latches [34]. This will probably be a cheaper solution if we assume that the TDCs are used for cosmic ray rejection only. As mentioned above though some analyses use the exact timing information from the TDCs. One could alternatively imagine building TDCs for the hadron calorimeters and latches for the EM calorimeters. In this case the latch gate would probably be a few ns wide.

12 XII. Cost Estimates

The cost estimate I am using here is the one we have from P.I.G. as of April 1993 [35]. The cost estimate has to be updated as soon as possible so that we can make a fair decision when we put the physics issues against the cost of the TDCs. This cost estimate assumes one TDC channel on every calorimeter tower. The circuitry resides in a) front end analog crates and b) in the VME memory cards.

As far as memory cards are concerned:

For the plug upgrade calorimeter, both PHAU and PEMU, we would need 64 cards with 32 channels each. These cards cost $\sim$ 2.5 K \$ each and the cost includes Memory, Logic, PC board, 8 bit TDC and analog parts. Therefore it would be $\sim$ 160 K \$ for the memory cards in the plug calorimeter. This amount is approximately equally divided between PHAU and PEMU.

For the Central calorimeters we assume here that we TDC each wedge separately, that is we do not have in the same TDC card channels from different wedges. In this case:

For CHA we would need 48 cards of 32 channels and the cost would be $\sim$ 120 K \$.

For CEM we would need 48 cards of 32 channels and the cost would be $\sim$ 120 K \$.

For WHA we would need 24 cards of 32 channels and the cost would be $\sim$ 60 K \$.

One reason we need so many more TDC cards for the central calorimeter is that many cards are almost empty. If we want to follow the current scheme and TDC the wedges separately, we should not have to use 32 channel cards. We can use cards with smaller number of channels. According to C. Nelson 2 cards of 16 channels cost roughly $\sim$ 25% more than one card of 32 channels. Of course we should also consider the possibility of having more than one wedges on the same TDC card.

As far as front end analog crates are concerned, it looks like that if we decided to put TDCs only at CHA/WHA we would save 108 K \$ in front end analog cards. If we want though to be able to add the TDCs at the rest of the calorimeters at a later stage, we would have to spend this amount of money right away if we follow scheme b) of section IX.A. This is so because the time circuitry has to be included in the same package as the charge circuitry. If we follow scheme a) we can probably stage the 108 K \$. For Scheme c) we can probably stage it as well, but this issue has to be clarified with P.I.G..

A couple of more points to consider are that:

a) If we want to have a two hit TDC instead of a one hit, then probably we are looking at an increase at the cost in the order of a factor of two. This is so because we will essentially double the read out channels and the cost gets driven quite a lot by the read out cards.

b) If we follow a scheme in which we have separate cards for the TDCs and the ADCs and we put one TDC per trigger tower (2 physical towers) instead of one per physical tower, then we should assume a reduction in the cost of the TDCs on the order of a factor of 2. The reduction factor would not be that big if we have TDCs and ADCs at the same VME card.

13 XIII. Conclusion (personal)

1) CHA/WHA TDCs were important in our analyses in the previous runs and although their rejection power is expected to be reduced they will continue to be a useful handle in Run II and beyond. We have to try to improve their rejection power by narrowing their in-time window as much as possible.

2) CEM TDCs would be helpful. There are physics topics with photon+ $\not{E}_t$ signatures for which EM TDCs will be a unique handle. One has to admit that in the majority of these topics the model we try to test can be checked as well with some other signature that does not neccessarily need EM TDCs. A bigger help of the CEM TDCs could be the gaining back, we hope, of some of the rejection power of the HTDCs that will be lost in the future [36].

3) PHAU TDCs are recommended. Since with the new plug calorimeter we want to improve and extend our physics capabilities in the plug and forward regions, timing information in those regions will become crucial. The fact that our tracking is poorer in this region makes the timing information from the calorimeter even more important.

4) PEMU TDCs are the lowest in priority, but they would be helpful if it turns out that we have enough funding for them.

Since the cost of the TDCs will play a crucial role in the final decision of implementing them or not, it is important that we reach as soon as possible a decision on which of the schemes of section IX will be used and what will be the cost.

Because of the nature of this work I had to communicate with lots of people in the exotics, QCD and electroweak groups and also with people working with the muon systems, with the Particle Instrumentation Group, with people in the calorimeter/electronics Upgrade group and with people at the Fermilab Theory Department. I appreciate useful discussions with all of them. I would especially like to thank Steve Kuhlmann who worked with the HTDCs from their construction and with whom I had several useful discussions on the subject.

References

[1] F. Abe et al., Nucl. Instrum. Methods **A271**, 387 (1988).

[2] S. Kuhlman, C$DOC:HATFLT.MEM

[3] S. Kuhlman, Ph.D thesis, "Inclusive Central Jet Production at $\sqrt{s} = 1.8$ TeV", 1988.

[4] Steve Kuhlmann, CDF note 581, February 2 1991.

[5] Steve Kuhlmann, A. Garfinkel, CDF note 413, March 4 1986.

[6] T. Hessing, Ph.D thesis, "A Search for Quark Compositness with the CDF Detector at the Fermilab Collider", 1990.

[7] P. Hu, Ph.D thesis, "Search for Supersymmetric Particles in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV", 1990.

[8] F. Abe et al., Phys. Rev. Lett. **69**, 3439 (1992).

[9] B. Hubbard, Ph.D thesis, "Fragmentation properties of jets produced in proton-antiproton collisions at $\sqrt{s} = 1.8$ TeV", 1989.

[10] R. Markeloff, Ph.D thesis, "An analysis of monojet data in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV", 1992.

[11] F. Abe et al., Phys. Rev. **D46**, 1889 (1992).

[12] J. Freeman and A. White, "Physics at Fermilab in the 1990's", Breckenridge, Colorado, Agust 15-24, 1989.

[13] H. Komatsu and J. Kubo, Phys. Letters **B157**, 90 (1985); M. Quiros, G. Kane and H. E. Haber, Nucl. Phys. **B273**, 333 (1986).

[14] ALEPH Collaboration, Phys. Rep. **216**, 253 (1992); DELPHI Collaboration, P. Abreu et al., Nucl. Phys. **B373**, 3 (1992); L3 Collaboration, O. Andriani et al., Phys. Lett. **B303**, 391 (1993); CERN-PPE/93-30 (1993); OPAL Collaboration, M. Akrawy et al., Phys. Lett. **253**, 511 (1991).

[15] S. L. Wu et al., in "Proceedings of ECFA Workshop on LEP 200", Aachen, 1986, eds. A. Bohm and W. Hoogland, CERN 87-08, Vol. II, p. 312.

[16] T. Weiler, in "Collider Physics: Current Status and Future Prospects", Proceedings of the eighth Vanderbilt International Conference on High Energy Physics, Nashville, Tennessee, 1987, eds J. Brau and R. Panvini (World Scientific, Singapore, 1988), p. 219; H. Pois, T. Weiler and T. C. Yuan, Phys. Rev. **D47**, 3886 (1993).

[17] V. Barger, N. Deshpande, J. Hewett and T. Rizzo, OITS-499 (1992).

[18] P. Bamert and Z. Kunszt, Phys. Lett. **B306**, 335 (1993).

[19] A. Stange, W. Marciano and S. Willenbrock, FERMILAB-PUB-93/142-T.

[20] L. Dalmonte, G. Drake, S. Kuhlmann, C. Nelson, **CDF** note 282, February 18 1985.

[21] G. Redlinger, Y. D. Tsai, **CDF** note 521, June 26 1987.

[22] The ADC gate width for 400 ns operation will depend on the beam structure for which we do not have yet official documentation from the Accelerator group.

[23] I would like to thank H. Jensen at this point who asked the question: "How much cosmic ray rejection would the TDCs give us in run II and beyond? Do we really need them?", which made me investigate the issue further.

[24] S. Hahn, private communication.

[25] J. Lewis **CDF** note 2191, August 20 1993.

[26] This section has been extensively discussed with G. Drake and C. Nelson.

[27] Pawel de Barbaro, private communication.

[28] J. Strait, private communication.

[29] J. Strait, TS-DET 93-021, 22 April 1993.

[30] Pawel de Barbaro, private communication. Although the PEMU uses 4mm scintillator instead of 6mm of the PHAU and in principle it should have smaller number of pe's per layer, it has smaller tiles and therefore it provides more light. The actual measurement will be done within a few days.

[31] W. Koska, private communication.

[32] J. Proudfoot, R. Wagner, private communication.

[33] F. Abe et al., Phys. Rev. **D41**, 2330 (1990).

[34] A. Mukherjee, private communication.

[35] C. Campagnari, C. Newman-Holmes, private communication.

[36] In Run IB we could quantify to some extent the power of the CEM timing information against cosmics. According to H. Keutelian and A. Mukherjee we have $\sim$ 120 free TDC (LeCroy 1879) channels in the CTC readout system that we could use to get timing information from the CEM trigger towers. These data would get stored in the CTCD bank. Since we have about 250 CEM trigger towers, we would have the capability to either get timing information from 50% of them or test a smaller fraction using different discriminator thresholds. All the hardware modifications needed for the test could be restricted in the first and second floor of the B0 electronics rooms.

Figure Captions

1) Jet events. Time response of CHA wedges vs the energy in the wedge.

2) Photon P_T distribution from a prompt photon sample. The histogram corresponds to no cut and the triangles correspond to a cut of 3 on $\sigma_{\not{E}_t}$.

3) Fraction of jet backgrounds vs E_t.

4) CHF vs EMF.

5) CHF vs $\sigma_{\not{E}_t}$.

6) $\sigma_{\not{E}_t}$ vs EMF.

7) The calorimeter time difference between pairs of tracks from a sample of $\bar{p}p$ interactions (dashed line) and for a sample of cosmic rays (solid line). The shaded entries indicate events in the data sample used in this analysis which failed the cosmic ray cuts and were consequently removed from the sample.

8) Time relative to $\beta = 1$ particles vs energy deposition in the hadron calorimeter for the high-P_T data sample used for this analysis. The signal regions for massive $Q = 2/3$, $Q = 1$, and $Q = 4/3$ stable particles are indicated by the dotted, solid and dashed lines respectively. Note the suppressed zero.

9) Branching ratios of bosonic Higgs to $\gamma\gamma$, WW^*, ZZ^* vs the Higgs boson mass. The * denotes a virtual boson.

10) The charged fraction of the leading cluster in the monojet candidates (histogram) after removal of cosmic ray and beam gas background, and the charged fraction of the leading cluster in dijet events (data points) normalized to 217 events (226 candidates - 9 residual background).

11) Pulseheight distribution vs time for signal from the PHAU calorimeter.

: Histogram Display

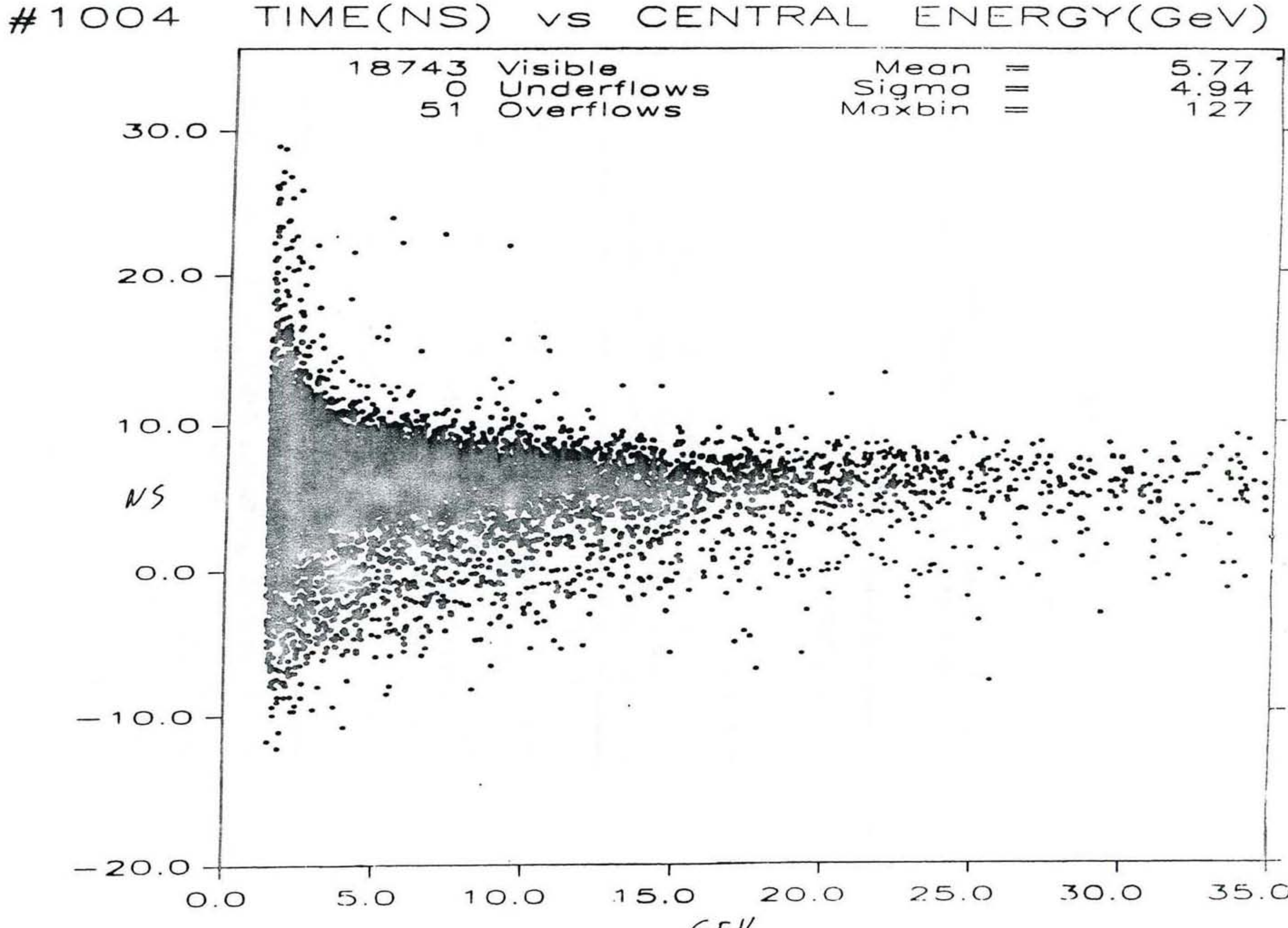


Figure 1

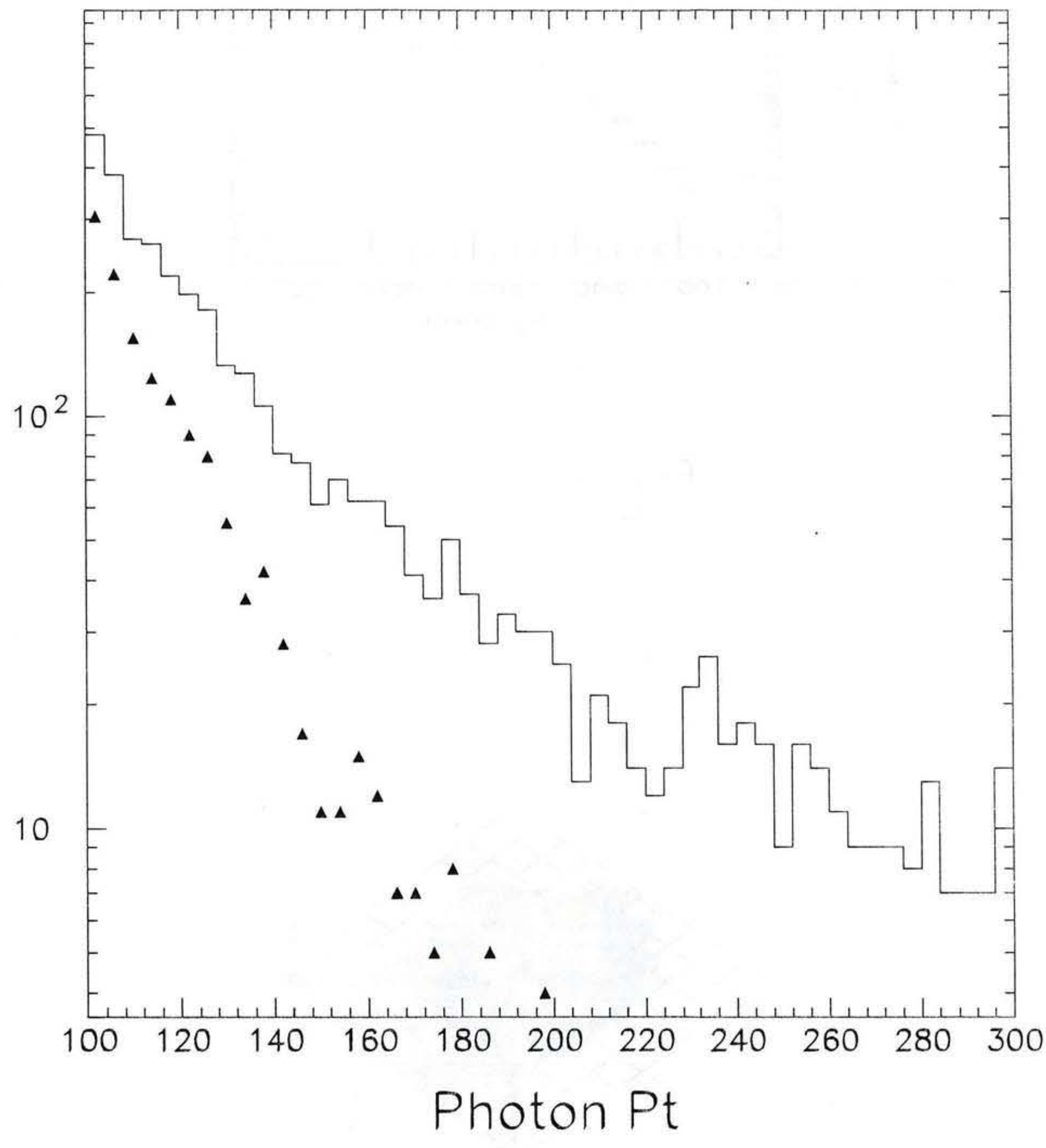


Figure 2

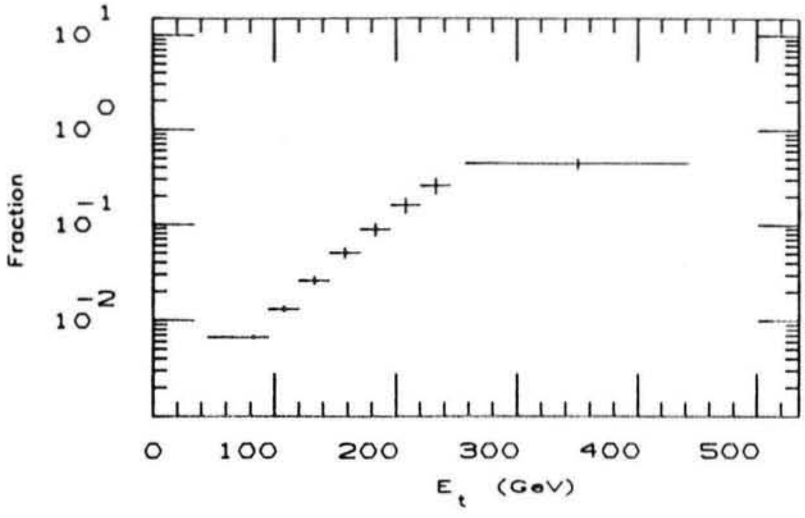


Figure 3

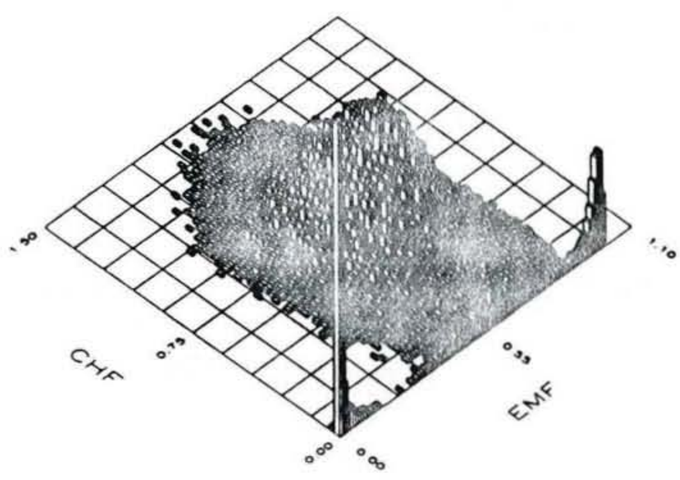


Figure 4

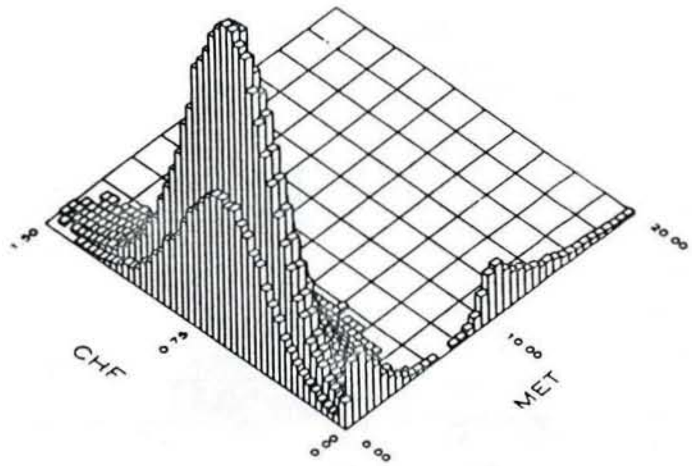


Figure 5

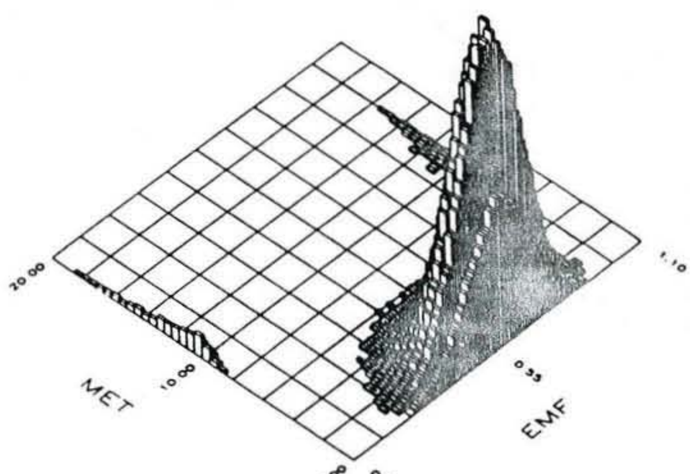


Figure 6

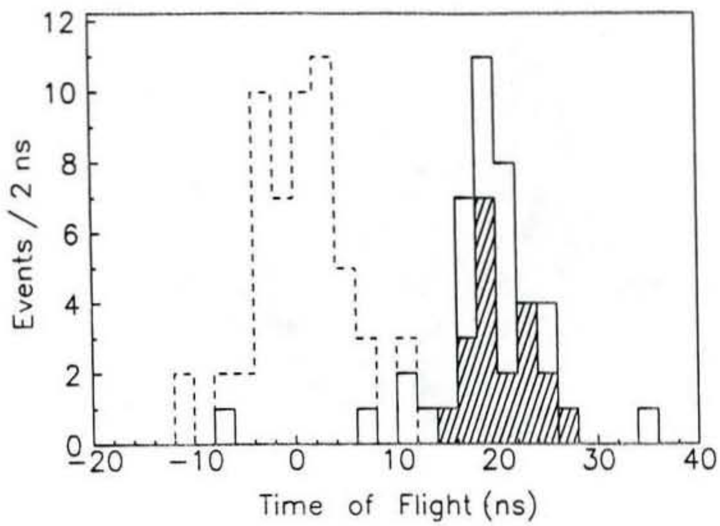


Figure 7

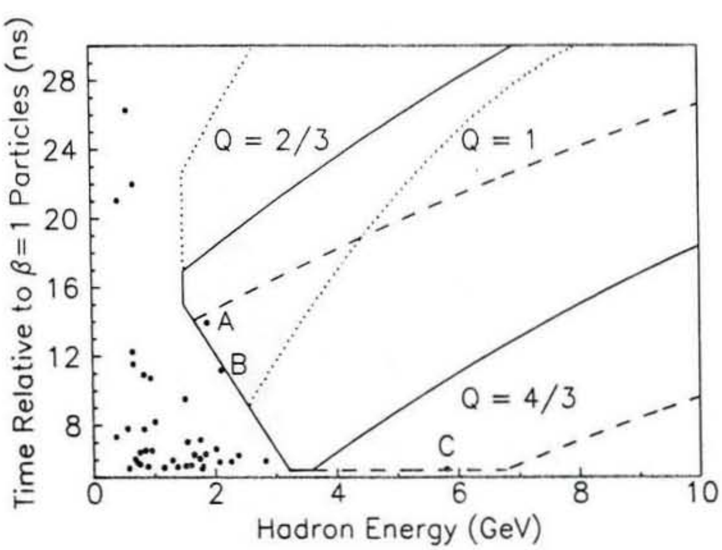


Figure 8

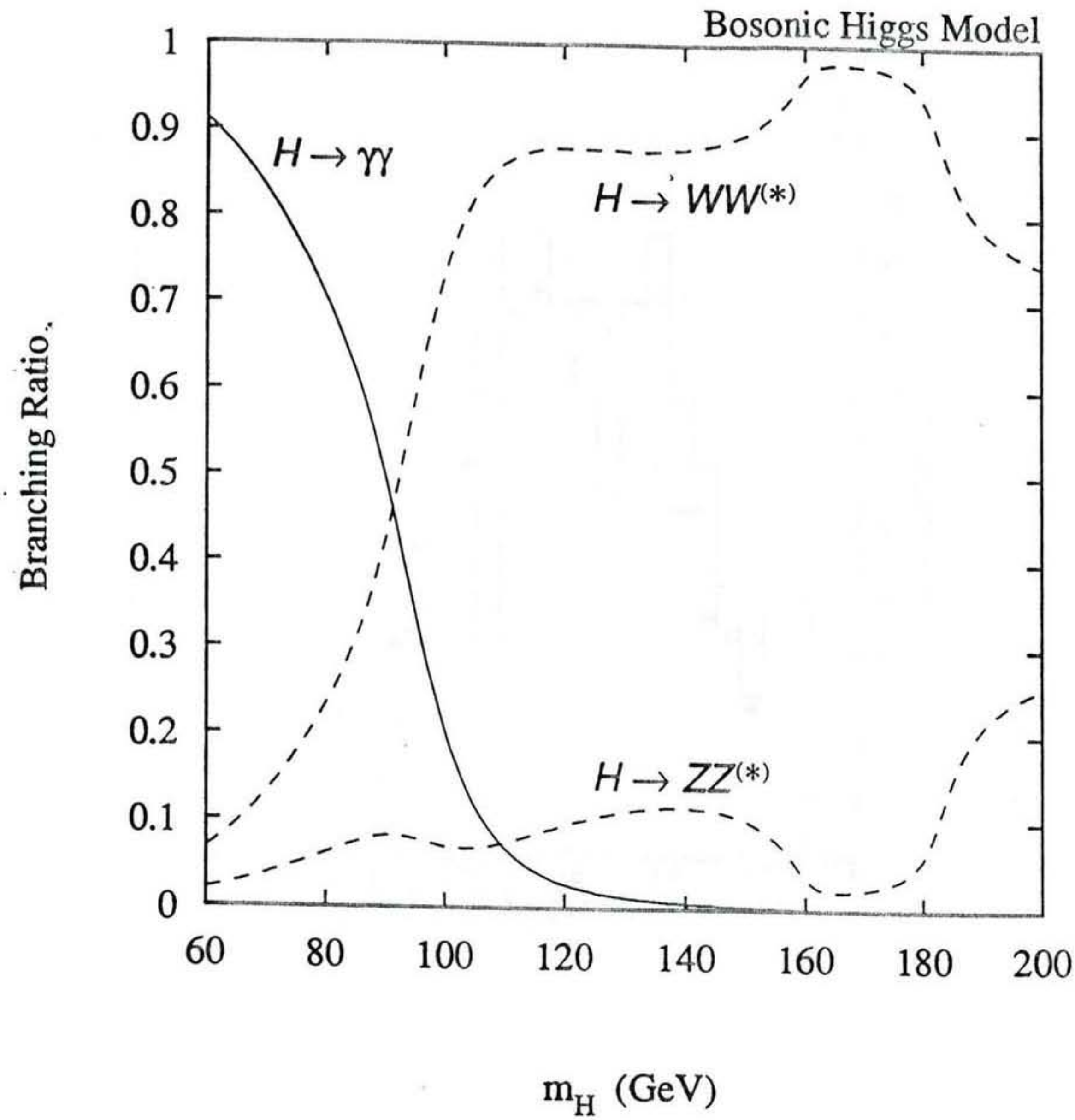
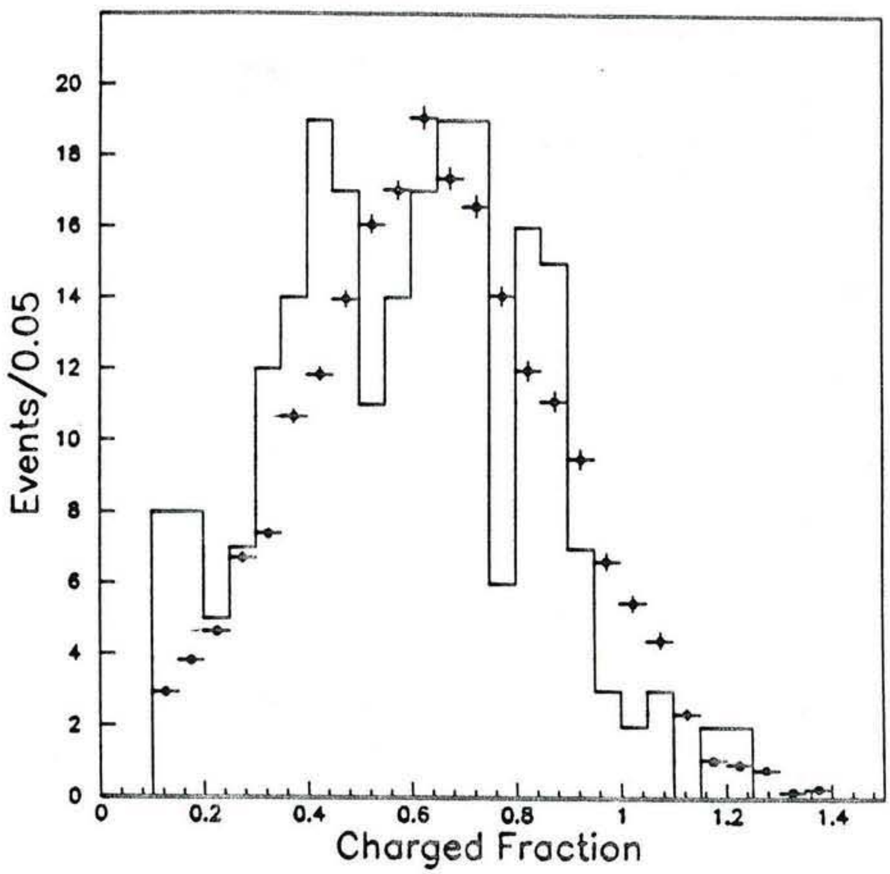

Bosonic Higgs Model
Branching Ratio
$H \rightarrow \gamma\gamma$
$H \rightarrow WW^{(*)}$
$H \rightarrow ZZ^{(*)}$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
60
80
100
120
140
160
180
200
m_H (GeV)

Figure 9



Events/0.05
Charged Fraction
0
0.2
0.4
0.6
0.8
1
1.2
1.4
2
4
6
8
10
12
14
16
18
20

Figure 10

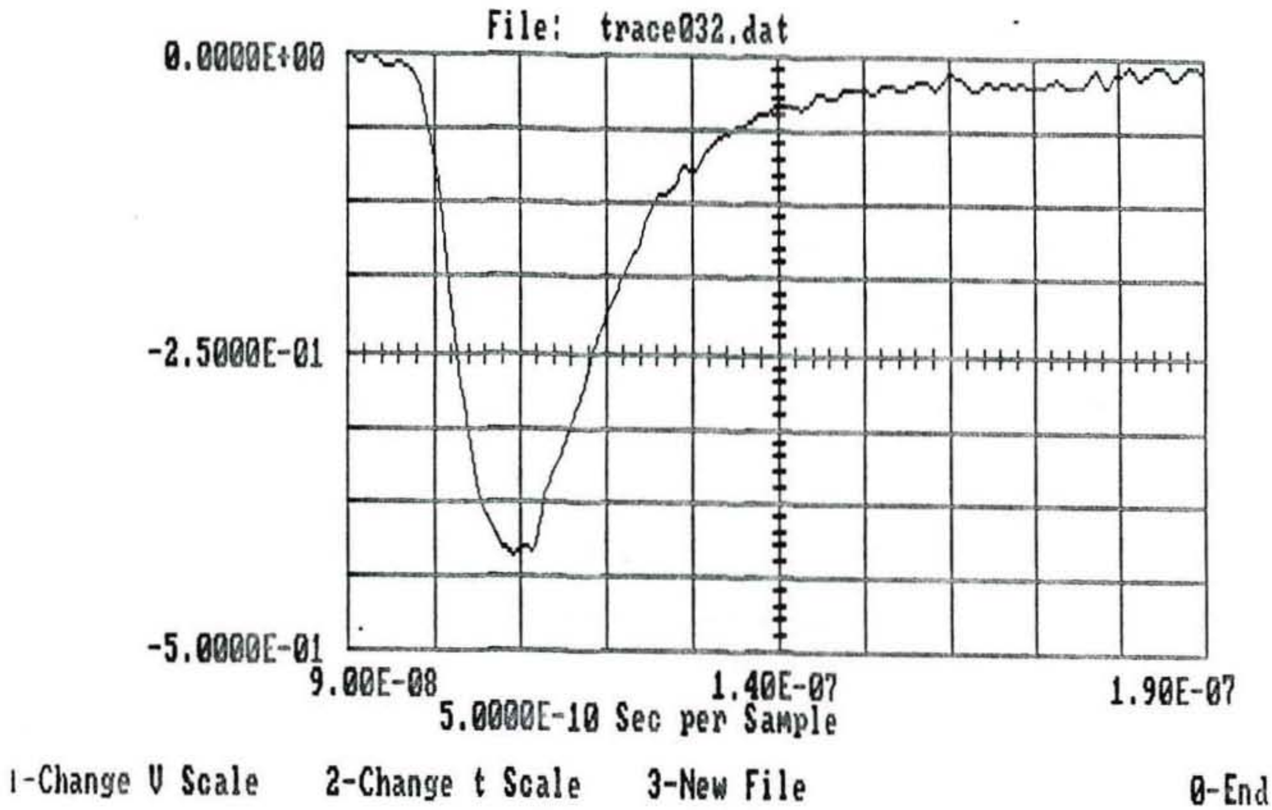

File: trace032.dat
0.0000E+00
-2.5000E-01
-5.0000E-01
9.00E-08
1.40E-07
1.90E-07
5.0000E-10 Sec per Sample
1-Change V Scale
2-Change t Scale
3-New File
0-End

Figure 11