THE CDF MUON SYSTEM

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We describe the characteristics of the CDF muon system and our experience with it. We explain how the trigger works and how we identify muons offline. We also describe the future upgrades of the system and our trigger plans for Run IB and beyond.

1. Description of the CDF Muon System

The CDF muon system consists of four subsystems: The Central MUon chambers (CMU), the Forward MUon chambers (FMU), the Central Muon uPgrade chambers (CMP), and the Central Muon eXtension chambers (CMX). The first two subsystems were parts of the detector from the 1987 collider run. The last two were added only in 1992, for Run IA (See Figure 1 Top. Figure 1 Bottom shows the detector in the Run II configuration).

CMU:

The CMU system is located around the outside of the central hadron calorimeter at a radial distance of 3.47 m from the beam axis. It is segmented in ϕ into 12.6° wedges which fit into the top of each 15° central calorimeter wedge. This leaves a gap in the central muon coverage of 2.4° between each wedge. Each muon wedge is further segmented in ϕ into three modules of 4.2° each. Each of the three modules consists of four layers of four rectangular drift cells. A stainless steel resistive 50 μm sense wire is located at the center of each cell. The chambers measure four points along the trajectory with an accuracy of 250 μm per point in the ϕ direction. Charge division gives an accuracy of σ =1.2 mm per point in the z direction. The chambers cover the angular region $56^o < \theta < 124^o$ or $|\eta| < 0.63$. In this region their average coverage is 84% due to the ϕ gaps between the wedges and the boundary between the central arches at $\theta = 90^o$. Because there is an average of only 5.4 pion interaction lengths between the CMU chambers and the event vertex, about 1 in 220 hadrons traverses the calorimeter without interacting, thereby causing the hadron to be misidentified as a muon. Another limitation of the detector is its restricted θ coverage.

FMU:

The CDF forward muon system consists of two muon spectrometers measuring muon momentum and position for polar angles 3^o-16^o (forward) and 164^o -177^o (backward). This system consists of a pair of magnetized iron toroids instrumented with three sets of drift chambers and two planes of scintillation trigger counters. We have an average of 17 pion interaction lengths in FMU and therefore there is no pion punch-through background. The main source of background in FMU is decays of pions and kaons in the space between the interaction point and the detector.

CMP:

The CMP consists of an additional 60 cm of steel absorber behind the current central muon system, followed by a second set of muon chambers. The return yoke of the CDF solenoid already provides the necessary steel at the top and bottom of the central detector so that it is only necessary to add more steel on the two sides, where two movable steel walls were installed. The CMP chambers have single wire drift cells. Four chamber layers are required, with one pair of chambers half-cell staggered relative to the other pair. CMP has a pseudorapidity coverage of $|\eta| \leq 0.57$ and has an average ϕ coverage of about 80%, so that the fraction of CMU also covered by CMP is 72%. It reduces the punch-through rate by a factor of ~ 10 (see Figure 2) which allows us to lower the p_T thresholds without the trigger rates becoming unmanageable, and also to identify muons within jets which is especially important for bottom and top physics.

CMX:

CMX consists of "pinwheels" of drift cells around each end of the detector. It extends the θ coverage by covering the region $.62 < |\eta| < 1.0$. In the region $-45^o < \phi < 225^o$ the cells lie on a conical surface to maximize the acceptance. In the region $225^o < \phi < 315^o$ the cells have been assembled in a flat pinwheel-like structure to minimize the space occupied. Because of the angle at which particles traverse the calorimeter, the amount of steel is larger here than in CMU and no new steel is added. We have 8 layers of drift cells between 2 layers of scintillator which provide three-dimensional tracking. The scintillators (CSX) provide the timing of the muon track. The cell dimensions are 1" x 6" x 72" and we have a single wire per cell. The resolution is 250 μm (1 cm) perpendicular to (along) the wire. Forty-eight cells are glued into a module covering 15^o in ϕ. Two arches with 8 modules each were installed on each side of the detector for Run IA. CMX covers currently 2/3 of ϕ; 30^o at the top of the detector have no coverage due to interference with the main ring shielding and the cryogenics. 90^o in the bottom were not instrumented either. We have an increase of approximately 25 % in the dimuon sample due to the dimuons that have one muon in the CMX.

3. Today: Run IA Triggers

CDF uses a three tiered trigger system. Level 1 (L1) has an input rate of 300 kHz, to match the 3.5 μs crossing time. Level 2 (L2) has an maximum input rate of approximately 2.5 kHz, and an output rate of about 20 Hz. Level 3 is a farm of computers that runs a slightly streamlined version of the offline reconstruction code, and can write about 6 Hz to tape.

At Level 1, we require either a single muon with a p_T above a high threshold, or two muons with p_T's above a lower threshold. For the central region, the high threshold is approximately 6 GeV, and for the extension it is 10 GeV. The low threshold is 3 GeV everywhere. Because the p_T is measured by the slope of the track in the muon chambers, with a lever arm of only a few centimeters, this measurement is cruder than measuring the transverse momentum in the central tracking chamber; the turn-ons are therefore rather soft.

In addition, if the muon is in a CMU chamber that is not in a CMP ϕ gap, there must also be a CMP hit for the muon to pass the high p_T threshold. Low p_T muons do not have this CMP requirement. The total Level 1 muon cross section is about 110 μb.

By Level 2, CTC tracking information in the $r - \phi$ plane is available from the CFT, or Central Fast Tracker. A track with $p_T > 9.2$ GeV is required to match within 5 degrees of the muon stub for a single muon trigger, and a track with $p_T > 3$ GeV is required to match within 15 degrees of one of the two muon stubs for a dimuon trigger. (The 15 degree requirement is there because there is not enough hardware to implement the 5 degree match on both sets of triggers.)

This dimuon trigger has two changes relative to the 1988-1989 run trigger, changes designed to increase the number of J/ψ's written to tape per unit luminosity. One change was to lower the trigger threshold at Level 2: in the 1988-89 run we required both muons to have $p_T > 3$ GeV/c; that requirement has been relaxed to requiring at least one muon to have $p_T > 3$ GeV/c. Figure 3 shows the substantial increase in J/ψ yield from this change. In the 1988-89 run we also required that the two muons be separated from each other by at least one full muon wedge. In Run IA, the separation requirement was reduced to a singe muon chamber This change increased the acceptance by approximately a factor of ~ 2 at high p_T's, for a combined trigger efficiency increase for J/ψ's of approximately a factor of five. Figure 4 shows the dimuon trigger efficiency plotted against muon p_T for the Level 1 trigger; Figure 5 shows the same thing for the Level 2 trigger.

3. Experience with the CMX system

Making the CMX system work was not trivial. The CMX allocated trigger cross section for Run IA was 64 μb for Levell and 78 nb for Level2. In May 1992, though, we had 4000 μb at L1 and L2 was significantly above the allocated cross section as well. The excess of triggers was not associated with the main ring, since the triggers were azimuthally symmetric. The excess was not due to pion punch-through that we had not anticipated, since the triggers did not pile up at cracks in the calorimeter. It was not some kind of strange beam loss either, since we did not observe any kind of east/west (proton/antiproton) asymmetry. These convinced us that the triggers were coming from the $\bar{p}p$ interaction. One clue in the understanding of the problem was that there was no calorimeter energy associated with the triggers. This led us to think that the triggers might possibly be coming from interactions of low-angle particles in the beam pipe or in the forward calorimeter. In addition, these particles appeared to have extremely low momentum, and rates in the front and back sections of the CMX showed indications that a substantial fraction of these particles were ranging out in the chamber material. The secondary-interaction or "spray" hypothesis was further supported by the fact that there was much more activity in the inner surface of the endplug calorimeter in Run IA than there was in the 1988-89 collider run. If there was a spray of particles from the beampipe into the plug calorimeter, it could also affect the rates of CMX. Monte Carlo studies were performed which were successful in predicting the observed trigger rates. In August 1992 we were convinced that the problem was due to particles interacting in the beam pipe and in the forward calorimeter. The available solutions were: a) to change the beam pipe; b)since a particle coming from the beam pipe or the forward calorimeter is delayed by roughly ten or twenty nanoseconds respectively relative to particles coming from the interaction point, we could apply a tight time gate to the scintillator coincidence; c)request that the muon has fired the Hadron Calorimeter TDCs.

In February 1993 we replaced the old, 69 mil thick stainless steel beam pipe by a thin one which was 30 mils of Aluminum and the trigger rates were reduced by factors of 2-3. The addition of a tight time gate at the scintillators and the Hadron Calorimeter TDC requirement made finally the L1 trigger rates manageable in March of 1993.

4. Offline muon reconstruction

Although we identify muons at L1 by requiring a muon track, and at L2 by requiring that this muon track matches to a Central Tracking Chamber (CTC) track, we have to apply tighter cuts offline in order to reject background. We first request that there is less than 3-4 σ difference in position between each muon chamber track and its associated, extrapolated CTC track, in both $r\phi$ and z views where σ is the calculated uncertainty due to multiple scattering, energy loss, and measurement uncertainties. One can make similar requirements for the slope. We have not used slope cuts till now but we may do in the future. (The remaining difficulty arises from the effect of δ rays in the muon chambers causing a mismeasurement of the slope) These cuts have efficiencies greater than 98% while they reduce the background by a factor of approximately five. Depending on the analysis, we also perform isolation cuts by looking at the energy in a cone around the muons and other energy related quantities or we request that the muon has CMP confirmation. It is seldom easy to understand the efficiency of the calorimetric cuts and therefore they are usually avoided.

5. 1993: Run IB

In Run IB, the delivered luminosity is expected to double, and the trigger bandwidth at Level 2 and Level 3 will also (approximately) double. This means that the cross-section at Level 1 will have to be reduced by approximately a factor of two. To do this, we are adding the additional requirement that the hadron calorimeter TDCs show energy deposition within 30 ns of the interaction. A muon deposits approximately 1 GeV of energy in the central or endwall hadronic calorimeter, which provides sufficient light at the phototube to measure the time. This information is used offline to reject cosmic rays; the plan is to use it online as well, to reject all out of time backgrounds: cosmic rays, forward calorimeter albedo, spray from the beampipe, main ring-induced particles, etc. Additionally, the CSX scintillators on the CMX will also be required to be in time, to within a few nanoseconds, further reducing the out of time background. Applying these timing cuts reduces the cross-section by more than a factor of two, so we are using the additional available bandwidth to implement a so-called "η gap" trigger. Muons which are in the ϕ region covered by the CMP, but not the η region (rejected by the IA trigger) will be accepted at Level 1 if there is hadron TDC confirmation in the η region not covered by the CMP.

At Level 2, the total cross-section is approximately the same. However, the cross-sections of several triggers, including the single muon and dimuon triggers, is increasing with luminosity. To fight this, a number of changes will be made. First, the Level 2 CFT (Central Fast Tracker) thresholds will be made different for muons with and without CMP confirmation. CMU-only and CMX muons will have a 12 GeV threshold; these triggers are intended for electroweak and top physics. The CMU-CMP muons, however, will have their threshold *lowered* to 7 or 8 GeV. The rationale is to trade low purity muon triggers for higher purity triggers, thus decreasing the overall trigger rate and increasing the number of $B \rightarrow \mu + X$ events simultaneously.

For dimuons, more drastic steps must be taken. The current trigger, which requires only one of the two muons to have a CFT track with $p_T > 3$ GeV has a cross-section that grows considerably with luminosity. Many of these events have one real muon of $p_T > 3$ GeV, and one junk stub. Requiring a track to point to both muon stubs is expected to solve the cross-section growth problem. Unfortunately, requiring both legs to pass the $p_T > 3$ GeV threshold (the current CFT lower limit) removes 80% of the J/ψ's. To solve this, the CFT is being modified so that the lowest p_T threshold is 2 GeV. This 2-2 trigger should have approximately the same J/ψ rate as the Run IA 3-0 trigger. J/ψ's that pass this trigger will have decays even more symmetric than those that pass the 3-0 trigger; this may have implications for J/ψ polarization physics. It is also possible that we will be able to make a tighter track-stub matching cut (5 degrees instead of 15) in Run IB.

Level 3 will remain essentially unchanged. The p_T thresholds will be changed to reflect the new Level 2 thresholds, and it is possible that the tracking will be restricted to the region of ϕ that caused the trigger - e.g. on J/ψ triggers, the away side jet won't be tracked.

6. 1996: Run II and beyond

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) to increase the polar angle coverage for muons, as well as to reduce the decay in flight background by reducing the decay length. 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. We plan to use scintillator signals from the upgraded plug calorimeter as a L1 trigger. We may also be able to use the FMU scintillator signals but probably the occupancy will be too high at Run II and beyond. There are also thoughts of using timing information from the plug calorimeters at L1, if there is timing information available,

In the central region, hardware upgrades that had been started for Run I will be completed for Run II. In particular, the bottom portion of the central muon extension will be installed, and the ϕ gaps in the CMP will be filled. In addition, the CMU will be operated in proportional mode rather than streamer mode.

Also in Run II, the beam bunch spacing will decrease from 3.5 μs to 396 ns, in preparation for the 192 ns crossing time in the Main Injector era. The maximum drift time in the CMU chambers is about 700 ns, and the maximum drift time the CMP chambers is about 2 μs. So, establishing the correct t_0 becomes the critical new feature of the Run II trigger.

The CMP chambers will be surrounded by scintillators, called the "CSP" detector, for Central muon Scintillator uPgrade. (Slightly fewer than half the counters have been installed in the CDF collision hall to test the system in Run IB.)

These will be able to give a t_0 for high p_T muons. However, for B physics, we would prefer not to rely on the CMP/CSP for t_0 information, because of the more restrictive momentum requirement it imposes on muons from J/ψ decays. Two alternative sources of t_0 information have been identified: calorimeter TDCs and the planned new hardware tracker.

The proposed "XFT" (eXtremely Fast Tracker) hardware tracker will provide a set of tracks and estimates of their transverse momentum for each crossing. A dimuon trigger could be implemented by requiring two low p_T CMU stubs, and two XFT tracks of $p_T >\sim 1.5$ GeV matching to these stubs. The crossing with the two XFT tracks is taken to be the crossing of the dimuon event, and the time of that crossing is the t_0 of the interaction.

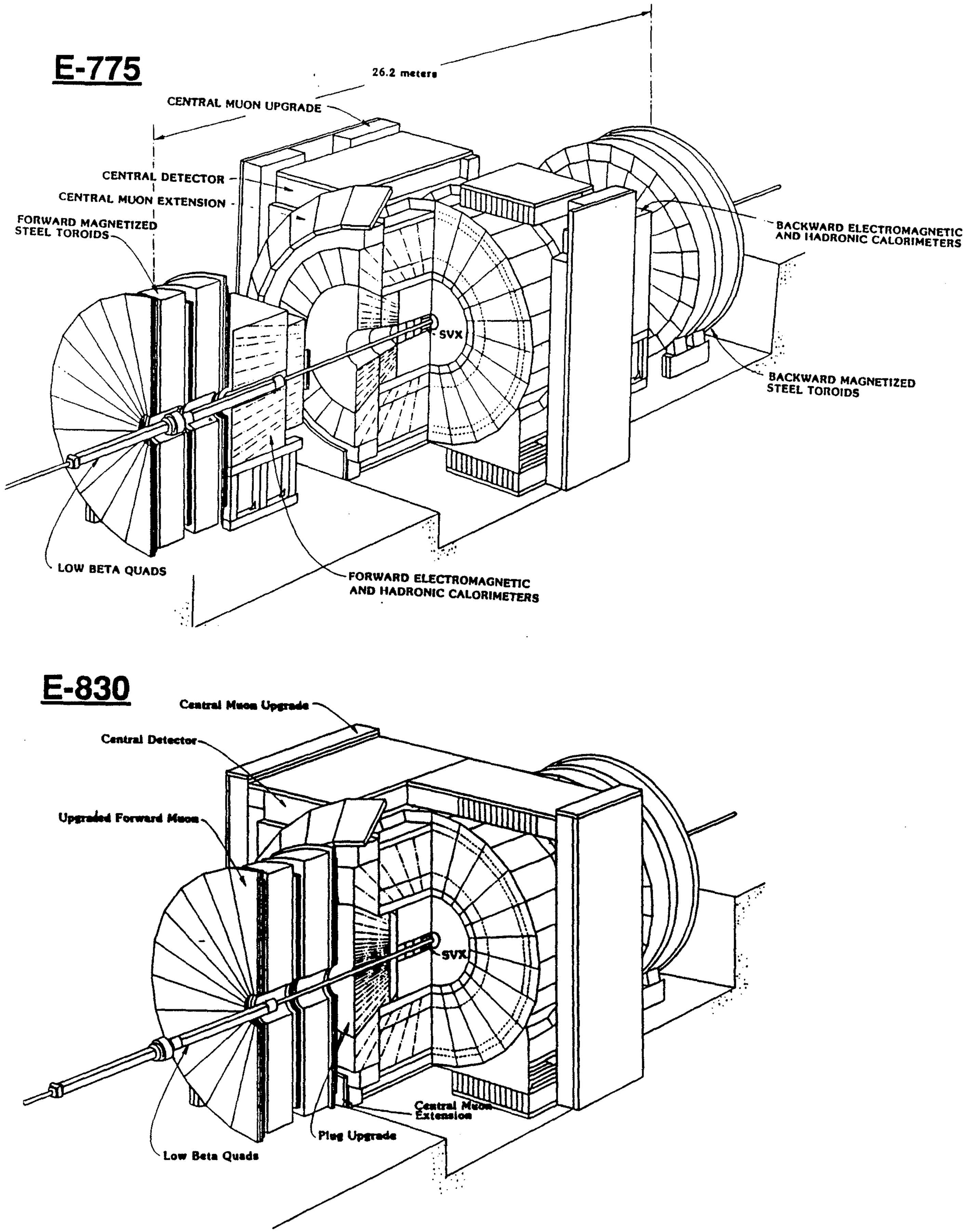
If difficulties arise in doing this, the alternative plan is to use TDCs on the hadron calorimeter outputs. This is more than sufficient to identify which 132 ns crossing caused the trigger.

Unlike Run I, the bandwidth is not really a limiting factor. The rates from the $B \to \pi^+\pi^-$ trigger overwhelm everything else. Planned thresholds are 1.5 GeV on each leg for dimuon triggers, 6 GeV for single muon triggers in the upgrade region (3 GeV if the muon has a large impact parameter as measured by the Level 2 vertex tracker), and 9 GeV for muons without CMP confirmation: again, for W, Z and top physics.

7. Summary

The CDF muon system, originally designed for electroweak and top physics, is capable of triggering on $B \to \mu + X$ and $B \to J/\psi + X$ decays. Since the 1989-1989 run, we have increased coverage with the addition of the CMX, purity with the addition of the CMP, and yields by lowering trigger thresholds. A rich program of investigating the physics of b's is already underway. The CDF strategy for the future is to continue increasing the coverage and triggering efficiency.

CDF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BACKWARD ELECTROMAGNETIC
AND HADRONIC CALORIMETERS
BACKWARD MAGNETIZED
STEEL TOROIDS
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Figure 1

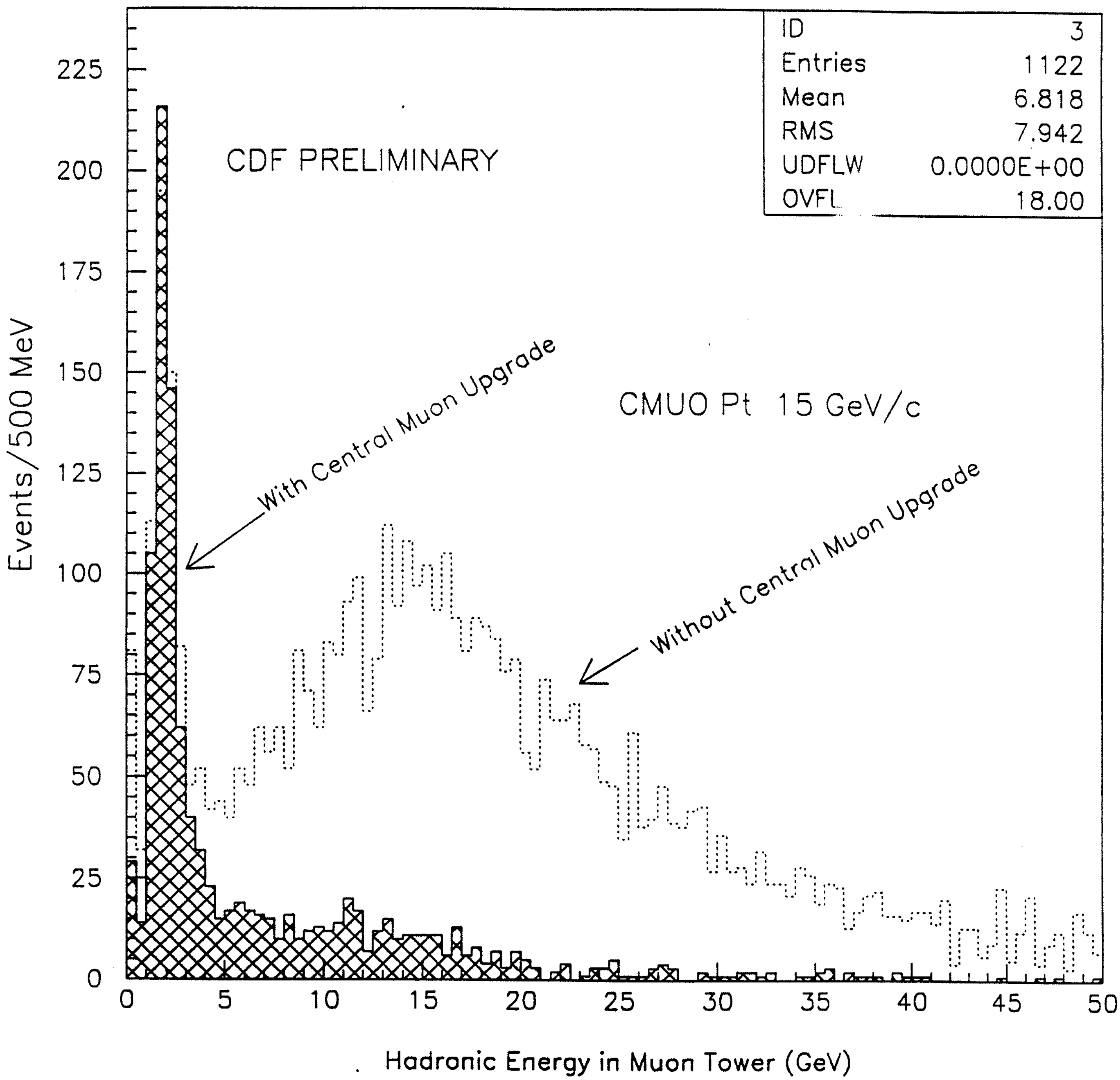

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Figure 2

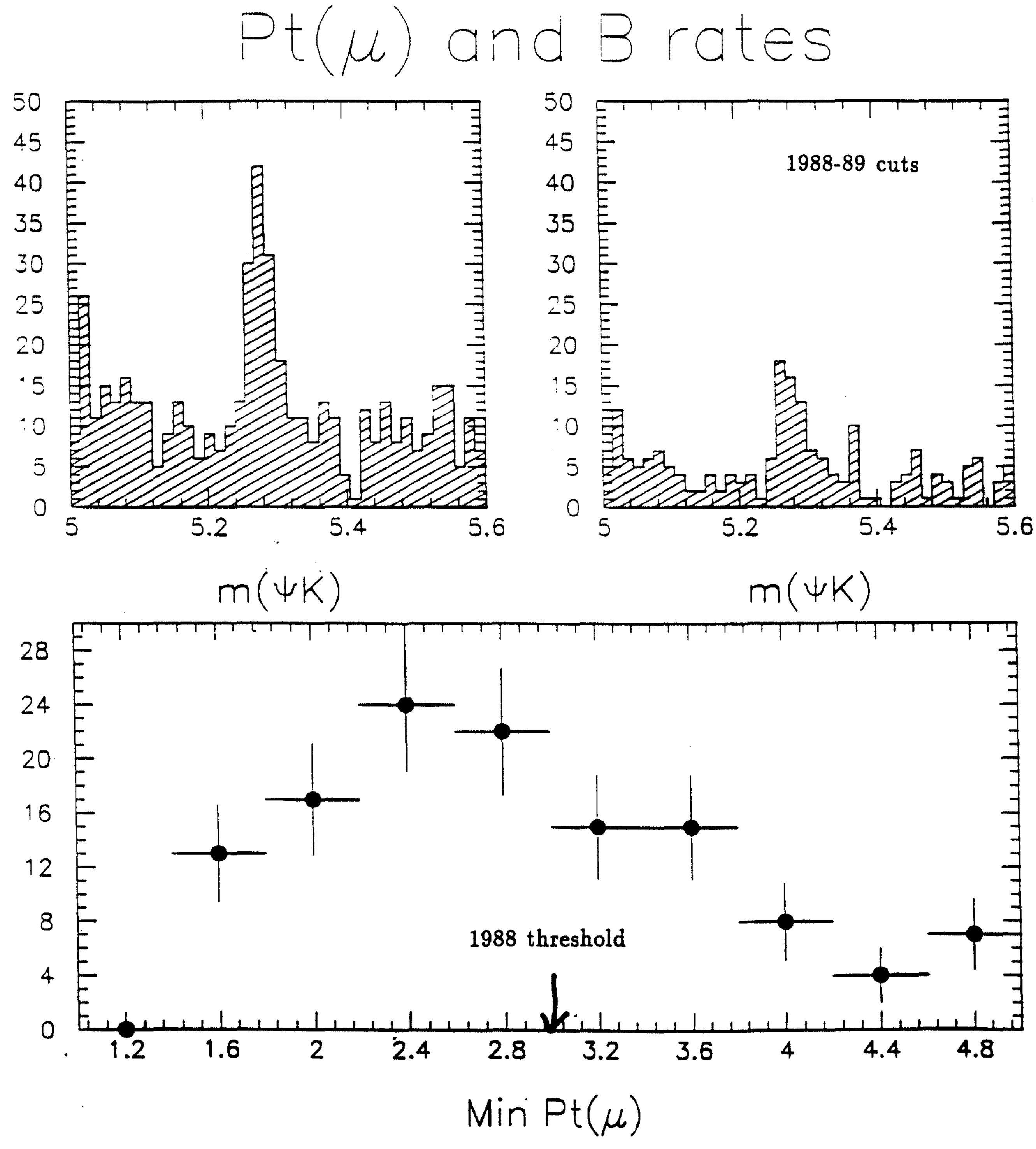

Figure 3

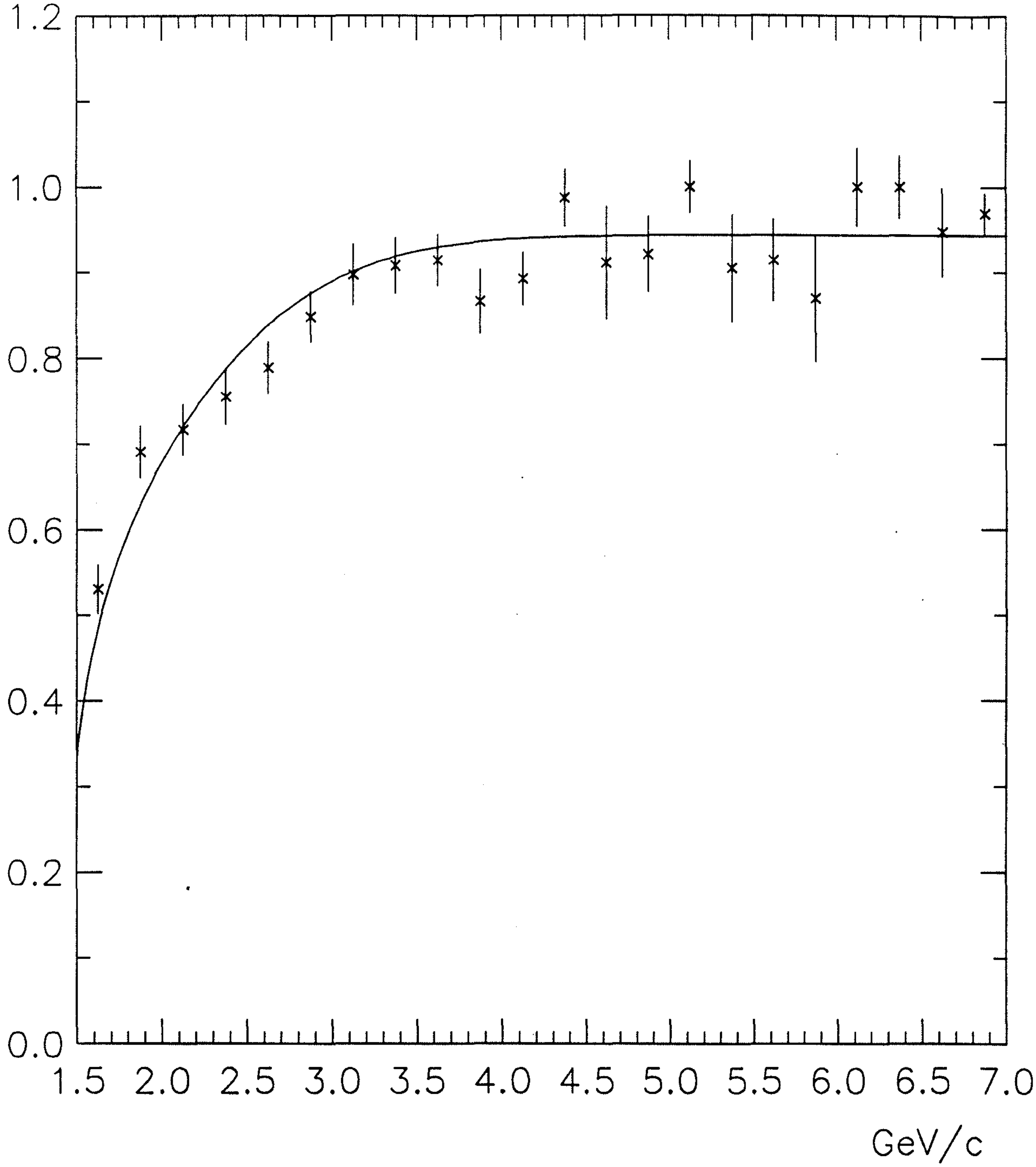

Figure 4

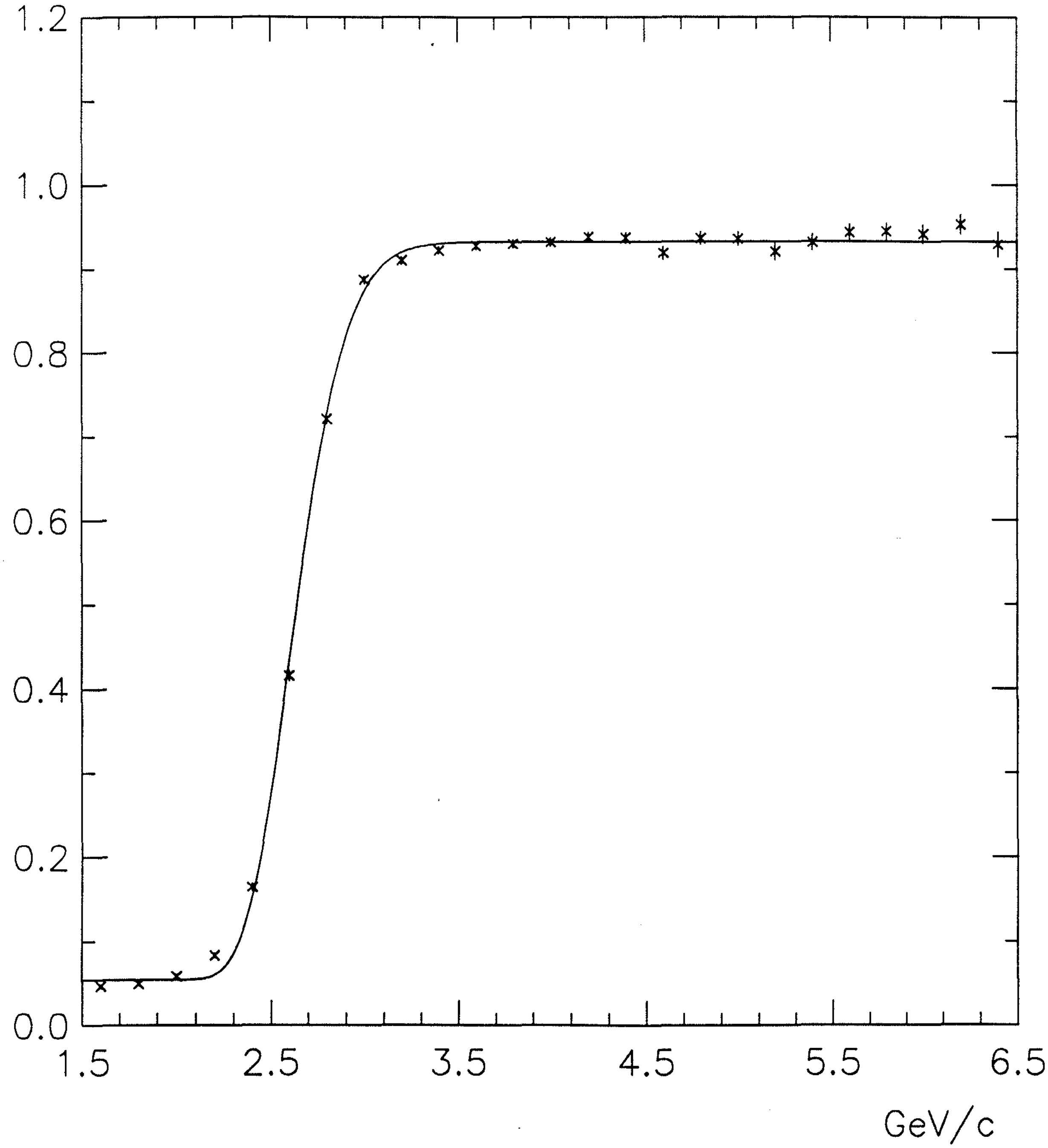

Figure 5