2 APPARATUS

Fermilab Experiment 866 used a modified version of the the dimuon spectrometer [Cri 86] located in the Meson East experimental area at the Fermi National Accelerator Laboratory. Previous experiments which used this spectrometer were E605, E772 and E789. Figure 2.1 shows a drawing of the E866 spectrometer, which was designed to detect oppositely-charged muon pairs while minimizing sensitivity to everything else. The coordinate system of the spectrometer was defined in the following way: the z-axis of the spectrometer was parallel to the nominal direction of the beam; the x-axis laid parallel to the floor of the experimental hall, pointing to the left facing station-1 from the targets; the y-axis then formed the right-handed Cartesian coordinate system by pointing up, perpendicular to the floor of the experimental hall. The origin of the coordinate system was chosen as the center of the upstream face of the SM12 magnet.

2.1 Beam line

An 800-GeV proton beam was extracted from the Fermilab Tevatron, split at the switchyard and sent to several fixed target experiments which ran concurrently during the 1996 fixed target run. The beam was transported down the east beam line of the Meson experimental area and arrived at the target in 20-second-long spills, with new spills arriving once every minute. The accelerator's frequency

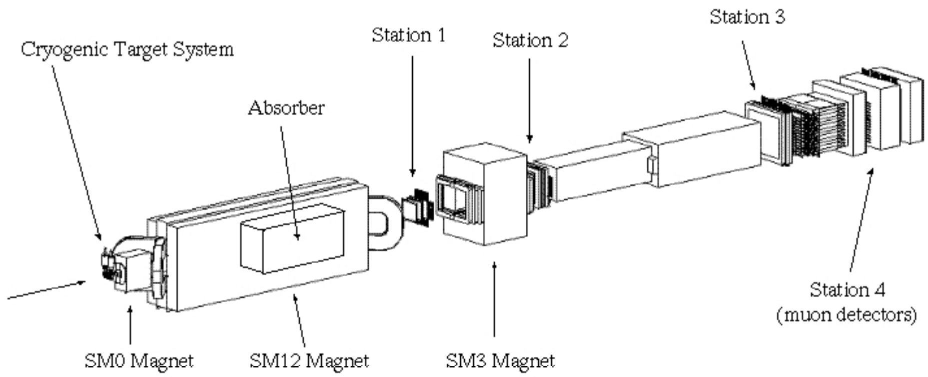

Figure 2.1: FNAL E866/NuSea Spectrometer.

was 53 MHz, which meant that during the spill the protons arrived grouped into "buckets" separated by 19 ns. The typical intensities which were used for E866 were between 1×10^{11} and 2×10^{12} protons per spill, depending on trigger rates and radiation-safety requirements for a particular spectrometer configuration.

The position, size and intensity of the beam was constantly monitored at various points along the beam line by several detectors. The beam's position and size were monitored by segmented wire ion chambers (SWICs). The last SWIC in the beam line was located approximately 188 cm upstream of the target. It had a 2 mm horizontal wire spacing and a 0.5 mm vertical wire spacing. During the experiment, the beam spot on the target was approximately 6 mm wide by 1 mm high.

Three different types of detectors monitored the intensity of the beam. The primary detector was a secondary-emission monitor (SEM), located at about 100 m upstream of the targets. In addition to the SEM counter, an ion chamber (IC3) and a quarter-wave RF cavity were used. These additional detectors allowed us to study the linearity and offsets of the SEM.

The luminosities of the targets were also monitored during the experiment with a pair of four element scintillator telescopes located about 85° from the beam direction in the horizontal plane. The data from these detectors (referred to as AMON and WMON) were used to determine beam duty factor, data acquisition live-time and which target was in the beam during the spill.

2.2 Targets

Three identical target flasks, one of which is shown in figure 2.2, were mounted on a movable table located at $z \approx -400$ cm. They consisted of a 17-inch long cylindrical shell with a 3-inch inside diameter. Hemispherical end caps with a 3-inch diameter sealed either end, creating a 20-inch (50.8-cm) long target along the beam axis[1]. Facing the targets from upstream, the leftmost target was filled with liquid hydrogen and the rightmost target was filled with liquid deuterium. The center target was empty and held at vacuum to measure the background rates due to the beam interacting with the SWIC, the material in the target flasks, and

[1] It was confirmed by visual inspection after the experiment that the z-axis of each target was aligned properly with the beam.

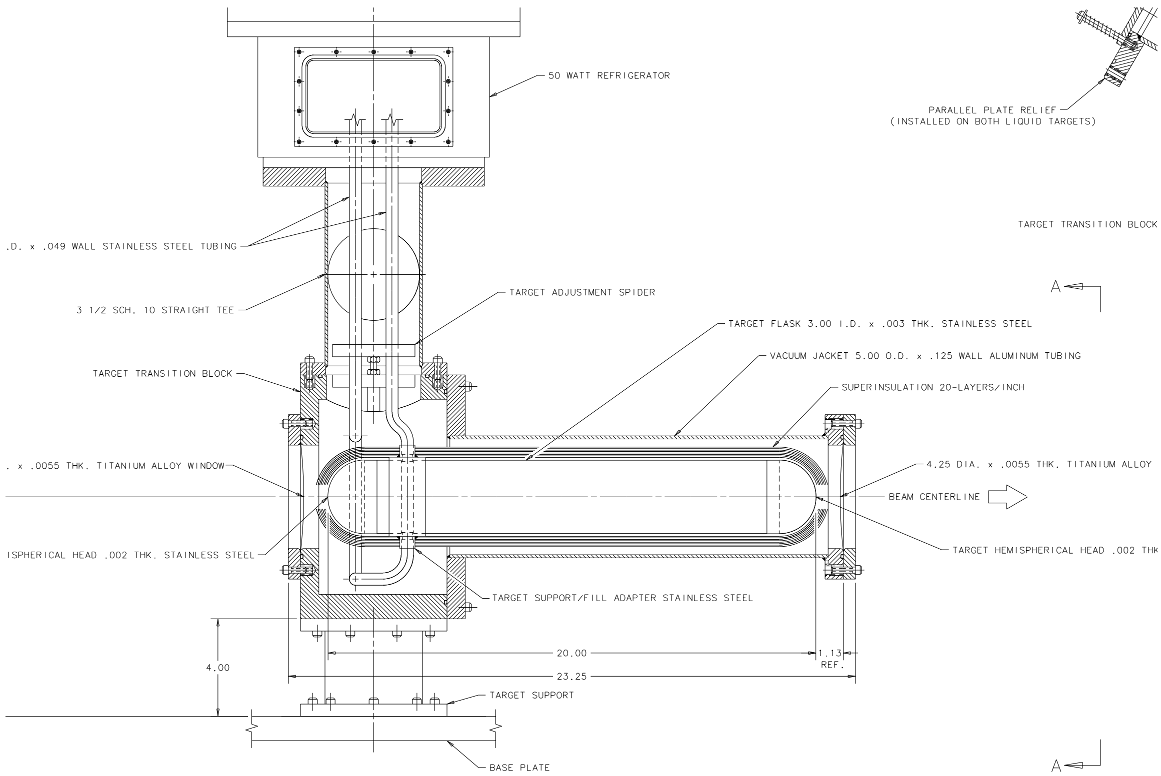

Figure 2.2: One of the three identical target flasks used in E866.

the air and other materials downstream of the target. Immediately downstream of the target, filling the aperture of the SM0 magnet, was a bag filled with helium to reduce background interactions in the vicinity of the targets.

The targets were cycled periodically to minimize the systematic uncertainties between the hydrogen and deuterium measurements. The programed sequence was 5 spills on the deuterium target followed by 1 spill on the empty target, 5 spills on the hydrogen target, and one more spill on the empty target. The target control computer counted only "good" spills – spills which the DAQ determined had a sufficiently large number of protons. Upon receipt of the appropriate number of good spill signals, which were sent after the end of the spill, the target-control computer initiated the move to the next target in the sequence. The move was completed before the beginning of the next spill.

A set of four switches on the target table were engaged by a stationary roller mounted in front of the table. The positions of these switches corresponded to the beam striking the center of each of the targets, plus a fourth position where the targets were clear of the beam. When engaged, each switch completed a circuit which was read out by the DAQ, recording which target was in the beam. The switches were also tied into the beam interlock system, which required that one of the four switches be engaged for beam to be allowed to enter the target area. This ensured that the beam would not be able to hit the sides of the target flasks and cause a radiation hazard.

2.3 Spectrometer Magnets

The E866 spectrometer used three dipole magnets whose magnetic fields were oriented in the x direction (bending charged particles in the y direction). The two magnets closest to the targets were SM0 and SM12. These magnets were used to optimize the acceptance of the spectrometer for different ranges of dimuon masses. The SM12 magnet was used to focus dimuon pairs on the downstream detector elements. Access to higher-mass events, which tend to have larger opening angles, was possible by using larger magnetic fields in SM12. This would ensure that such events were kept inside the aperture of the SM12 magnet and the detector stations.

The SM0 magnet was used to optimize the spectrometer for lower mass dimuon events in the low-mass data set. In this data set, the SM0 magnet was used to defocus (increase the opening angle of) the $\mu^+\mu^-$ pairs before they entered SM12. This increased the probability that the muons would miss the dump. More importantly, this increased the probability that the events would miss the dump cut used to eliminate beam-like muons, which were indistinguishable from the high flux of muons produced in the dump.

The SM3 magnet was located between the station-1 and station-2 detectors. It was used in the experiment to analyze the momentum of the muons by measuring the deflection it produced in the tracks. It was operated using a single current of 4230 A throughout the experiment.

2.4 Beam Dump and Hadronic Absorbing Wall

In order to prevent damage to the downstream detectors from the beam the target was followed by a large, water-cooled beam dump whose upstream face was located at $z \approx 173$ cm. The beam dump consisted of 255 cm of copper, which spanned -15.25 cm $\leq y \leq$ 15.25 cm at its thickest point. At its widest, the dump blocked the entire x-aperture of the magnet. The beam dump was nominally centered on the z-axis, but had settled over the years and developed a small slope relative to SM12 such that it was approximately $0.2''$ low at $z = 68''$ and $0.4''$ low at $z = 530''$.

A large hadronic absorbing wall was located immediately downstream of the beam dump. The purpose of this wall was to fully attenuate the intense flux of hadrons produced in the target and the dump. The absorbing wall consisted of 61 cm of copper[2] in the most upstream section, followed by a 205.8 cm section of carbon, a 68.6 cm long section containing both carbon and polyethylene, and a 183 cm section of polyethylene. The configuration of the beam dump and absorbing wall is shown in figure 2.3.

2.5 Detector Stations

Four detector stations were responsible for triggering on dimuon events and tracking the muons which traversed the spectrometer. The first three detector stations consisted of hodoscope- and drift chamber-planes, while station-4 consisted of hodoscope- and proportional-tube planes. The fast response time of the hodoscopes was utilized to trigger on events with the expected dimuon signature, at which point the slower responding drift chambers could be read out. The proportional-tubes and hodoscopes at station-4 were used to provide some position information to the trigger, and discriminate against any hadrons which made

[2] There was a 7.6 cm gap between the copper and carbon sections of the absorbing wall in the region behind the dump.

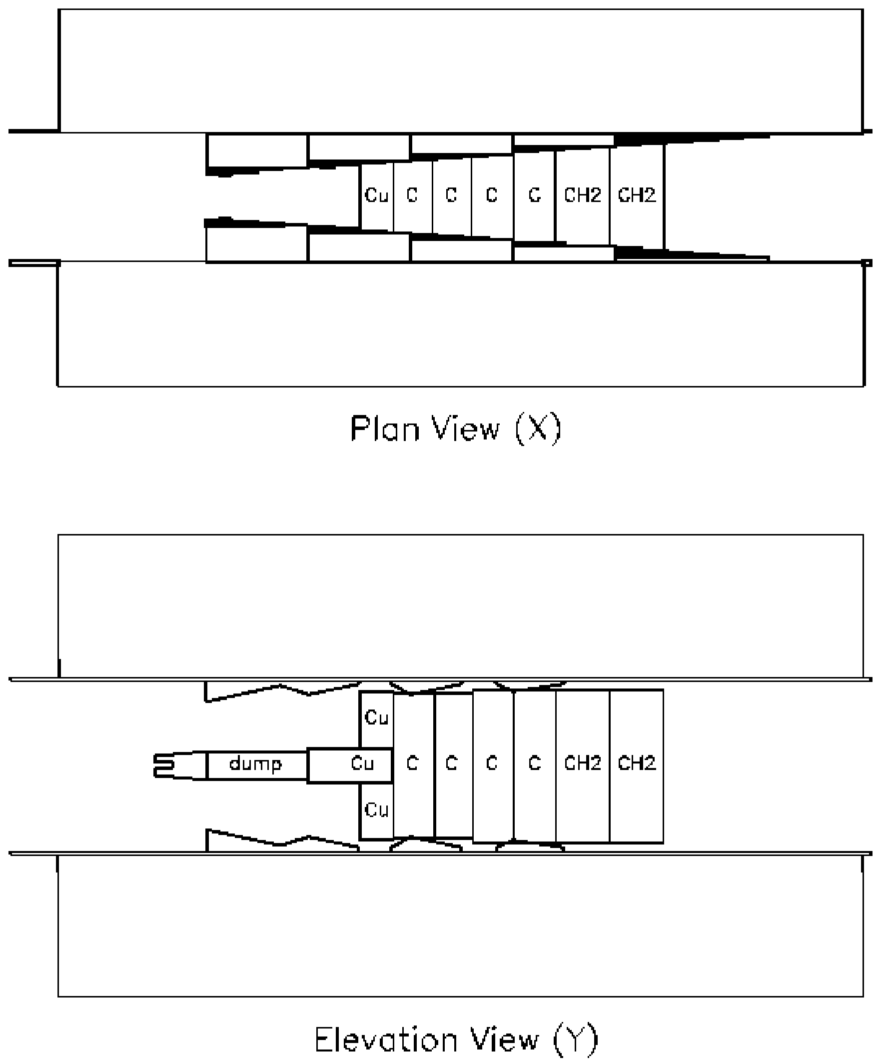

Figure 2.3: Side and elevation views of the absorbing wall and beam dump.

it through the absorbing wall.

2.5.1 Hodoscope Planes

Hodoscope planes were located at each of the four detector stations and were used to trigger on dimuon events. Each hodoscope plane was split into two half-planes of parallel scintillator paddles attached to photomultiplier tubes by plexiglass light guides. Stations 1, 3 and 4 each had two hodoscope planes, with their paddles oriented in the X and Y directions respectively. Station-2 had only one hodoscope plane, with its paddles oriented parallel to the floor. A vertical gap between the Y half-planes and the central X hodoscopes was inserted in order to avoid triggering on the high rate of beam-like muons from the decay of pions which were produced copiously in the dump. The design specifications of the hodoscope planes can be found in table 2.1. A more precise alignment of the hodoscopes was achieved by examining the distributions of positions of muon tracks at each hodoscope plane when a given hodoscope in that plane fired.

2.5.2 Drift Chambers

Each of the first three detector stations contained six drift-chamber planes, arranged in three pairs of planes with parallel wire orientations (referred to as "views"). Wires were oriented horizontally in the "Y" view, and at an angle of $+14°$ and $-14°$ with respect to the X axis in the "V" and "U" views, respec-

Table 2.1: Hodoscope specifications. Distances measured in inches.

detector	z position	# of counters	counter width	gap	Δx	Δy
Y1	769.78	16	2.5	0.38	47.50	40.75
X1	770.72	12	4.0	0.47	47.53	40.78
Y2	1114.94	16	3.0	0.66	64.625	48.625
X3	1822.00	12	8.68	1.0	105.18	92.00
Y3	1832.00	13	7.5	0.0	104.00	92.00
Y4	2035.50	14	8.0	0.0	116.00	100.00
X4	2131.12	16	7.125	0.0	126.00	114.00

tively. The wires in the second plane in each pair were offset by half the cell size of the drift chamber. The plane in each pair closest to the target was denoted as the "unprimed" plane, while the plane in the pair furthest from the target was denoted as the "primed" plane. These planes provide information on the X and Y intercept of the muon tracks at the detector station, with redundant information about the Y position.

The drift chambers were operated with a gas mixture of 49.7% argon, 49.6% ethane and 0.7% ethanol, mixed by volume at a constant temperature of 25°F. The anode wires at Station-1 were gold-plated tungsten wire. Stations 2 and 3 used silver-coated beryllium-copper wires as anodes. All of the anodes were 25 μm in diameter. The cathode wires were all 62.5-μm silver-coated beryllium-copper wire. The drift chambers were operated at voltages between 1700 and 2200 volts. Typical drift velocities were ≈ 50 μm/ns. Drift chamber specifications can be found in table 2.2.

The signals from the drift chambers were read out by a fast amplifier and discriminator system. Single-hit time-to-digital converters (TDCs), which only record the first hit on the wire during an event, were used to measure the drift time. The combination of good hits together with their associated drift times in all three views result in a "triplet" hit in each station. The bank of the triplets was saved to provide information used later in reconstructing the muon tracks in the analysis.

2.5.3 Proportional Tubes

The detectors at station-4 provided both trigger-information and muon discrimination capabilities. Located downstream of the electromagnetic and hadronic calorimeters[3], station-4 consisted of two hodoscope planes (X4 and Y4) and three proportional-tube planes (PTY1, PTX and PTY2). Each of the proportional-tube planes had two layers of 1×1-inch cells. Adjacent layers were offset by half a cell to cover the dead region between adjacent cells. The proportional-tubes were

[3] The calorimeters were left over from a previous experiment. For E866, they were unnecessary and were only used to eliminate any hadrons which made it through the absorbing wall.

Table 2.2: Drift chamber specifications. Distances measured in inches.

detector	Z-position	# of wires	cell size	aperture(X×Y)	operating voltage
V1	724.69	200	0.25	48×40	+1700
V1′	724.94	200	0.25	48×40	+1700
Y1	740.81	160	0.25	48×40	+1700
Y1′	741.06	160	0.25	48×40	+1700
U1	755.48	200	0.25	48×40	+1700
U1′	755.73	200	0.25	48×40	+1700
V2	1083.40	160	0.388	66×51.2	−2000
V2′	1085.52	160	0.388	66×51.2	−2000
Y2	1093.21	128	0.40	66×51.2	−2000
Y2′	1095.33	128	0.40	66×51.2	−2000
U2	1103.25	160	0.388	66×51.2	−1950
U2′	1105.37	160	0.388	66×51.2	−1975
V3	1790.09	144	0.796	106×95.5	−2200
V3′	1792.84	144	0.796	106×95.5	−2150
Y3	1800.20	112	0.82	106×91.8	−2200
Y3′	1802.95	112	0.82	106×91.8	−2200
U3	1810.24	144	0.796	106×95.5	−2200
U3′	1812.99	144	0.796	106×95.5	−2200

Table 2.3: Proportional tube specifications. Distances measured in inches.

detector	Z-position	No.of wires	cell size	aperture X×Y
PTY1	2041.75	120	1.0	117×120
PTX	2135.875	135	1.0	135.4×121.5
PTY2	2200.75	143	1.0	141.5×143

operated using the same gas mixture used in the drift chambers. To reduce the probability of any hadrons making it through the calorimeters, a 3 foot wall of zinc and a 4 inch wall of lead were placed between the calorimeters and the station-4 detectors. Furthermore, 3 feet of concrete was placed between PTY1 and X4 and between PTX and PTY2. This provided a total of 16.6 hadronic-interaction lengths upstream of the Y4 plane. The only detectable particles which could reach the station-4 detectors were muons. Specifications of the proportional-tubes may be found in table 2.3.

2.6 Trigger

Despite the fact that the absorbing wall all but eliminated the rate of hadrons produced in the dump, the rates of single and dimuon events from both the target and dump were too large for the drift chambers to be read out on every muon which was detected. Therefore the information from the hodoscopes was used to trigger on events which had the expected signature of a dimuon event originating in the target. The trigger was also configured to take prescaled samples of events which would be used later to reconstruct the combinatoric background.

The trigger system used in E866 was upgraded from that used for previous experiments [Gag 98]. The purpose of the upgrade was to increase the flexibility of the trigger, and to improve the acceptance of high p_T dimuon events. The main elements of the trigger system were the Trigger Matrix Modules and the Track Correlators. Figure 2.4 shows a diagram of the trigger electronics for the left hand side of the spectrometer.

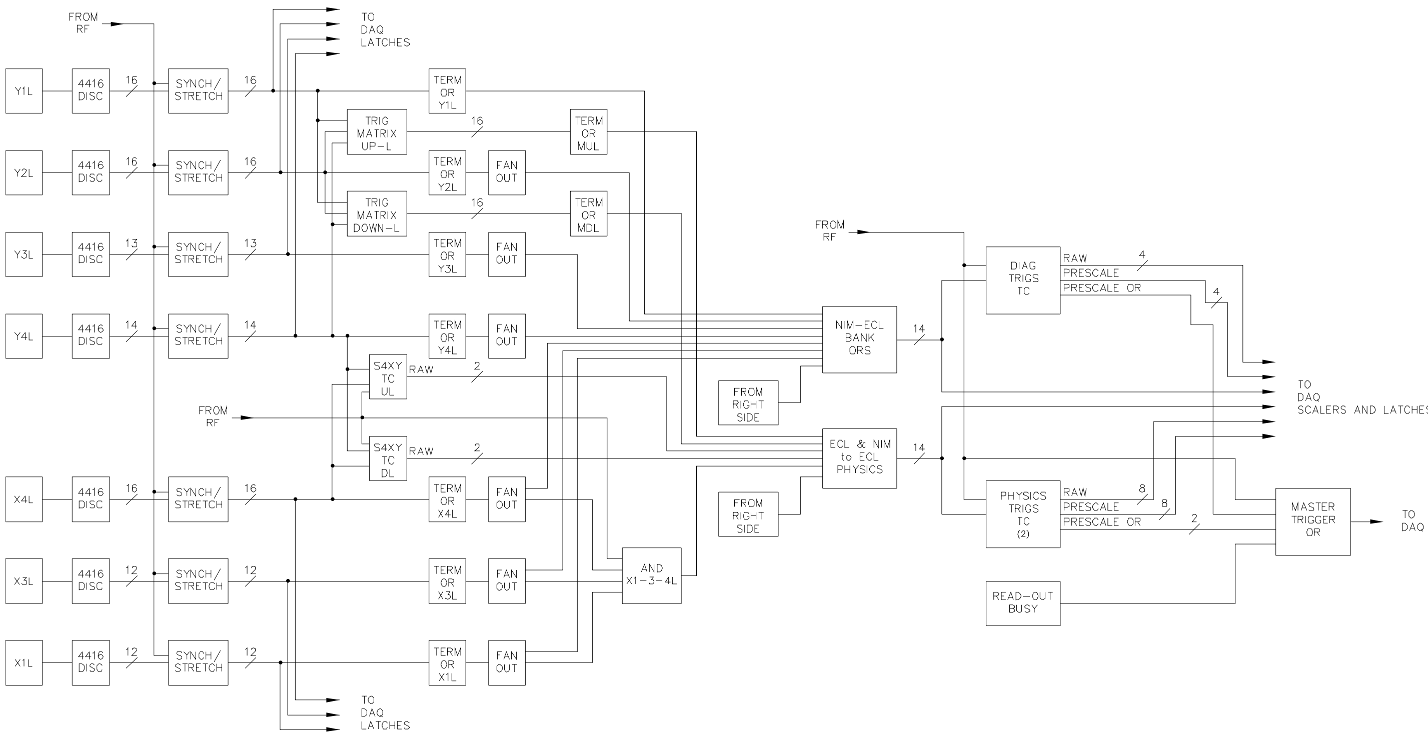

Figure 2.4: Block diagram of the E866 trigger. Only the inputs and electronics for the left side of the spectrometer are shown.

The Trigger Matrix Modules were responsible for determining whether a track was likely to be from a dimuon event which originated at the target. The outputs of the Y hodoscopes at stations 1, 2 and 4 were input into the Trigger Matrix Modules. The hit patterns registered by the hodoscopes were tested against a preselected set of hit patterns which corresponded to a muon from a dimuon event in the target traversing the spectrometer. These hit patterns where determined from Monte Carlo studies prior to the experiment. Some matrix elements had considerable rates of muons passing through them which actually originated in the dump. In order to take larger rates of target events, these matrix elements were turned off.

Four sets of Trigger Matrix Modules were used in the trigger system. These were referred to as matrix-up-left (MUL), matrix-down-left (MDL), matrix-up-right (MUR) and matrix-down-right (MDR). They corresponded to single muons on the left- or right-hand side of the spectrometer which went above or below the dump. These, along with the outputs of the Terminator/OR's and the Station-4 XY (S4XY) Track Correlators, were the inputs to the Track Correlators. The job of the Track Correlators was to filter the inputs and determine if a trigger should be fired and the event written to tape. There were three Track Correlators capable of triggering an event: Physics A, Physics B and Diagnostic.

Physics A (PhysA) was the main physics Track Correlator. Like all of the Track Correlators, it could handle four sets of trigger conditions. Table 2.4 shows the triggers that were used in each of the data sets in this analysis. The triggers in each of the data sets performed the same functions. The PhysA1 trigger selected oppositely-charged muons which traversed opposite sides of the spectrometer, while the PhysA3 and PhysA4 triggers selected oppositely-charged muons which traversed the same side of the spectrometer. The PhysA2 trigger was the like-sign trigger. It selected same-sign muon pairs on opposite sides of the spectrometer.

In addition to the requirements on the charge and geometry of the muons applied by the matrix, the Track Correlators used in the low- and intermediate-mass data sets added constraints on the X and Y positions of the muons at station-4 (the S4xxx entries in the table.) These constraints were designed to veto events which populated areas where the dump dominated the event rate.

The Physics B (PhysB) track correlator was used to sample events which were used to monitor the efficiencies and systematics of the detector. An example of one of the many B triggers used in the experiment appears in table 2.5. The PhysB1 trigger was designed to read out any event with muons traveling along paths on opposite sides of the spectrometer, regardless of their relative sign. The PhysB2 trigger was often configured to trigger on events with a single muon traveling along one of the predetermined matrix roads that a muon in a dimuon event would follow. These data were used to extract the combinatoric background, as will be discussed later.

Table 2.4: Trigger configuration (PhysA). Configurations shown for the low-, intermediate- and high-mass data. The symbols "*", "+" and "!" correspond to logical AND, OR and NOT, respectively.

Mass Setting	Number	Prescale	Requirements
low	PhysA1	1	(MUL * MDR) + (MUR * MDL)
	PhysA2	4	(MUL * MUR) + (MDL * MDR)
	PhysA3	1	(MUL * MDL) * (S4UL2 * S4DL2)
	PhysA4	1	(MUR * MDR) * (S4UR2 * S4DR2)
int	PhysA1	1	((MUL * MDR) * (!S4DL1 + !S4UR1)) + ((MUR * MDL) * (!S4DR1 + !S4UL1))
	PhysA2	2,1	((MUL * MUR) * (!S4DL1 + !S4DR1)) + ((MDL * MDR) * (!S4UL1 + !S4UR1))
	PhysA3	1	((MUL * MDL) * (!S4UL1 + !S4DL1) * (S4UL2 * S4DL2))
	PhysA4	1	((MUR * MDR) * (!S4UR1 + !S4DR1) * (S4UR2 * S4DR2))
high	PhysA1	1	(MUL * MDR) + (MUR * MDL)
	PhysA2	4	(MUL * MUR) + (MDL * MDR)
	PhysA3	1	(MUL * MDL)
	PhysA4	1	(MUR * MDR)

Table 2.5: Trigger configuration (PhysB). An example of a PhysB trigger used in the high-mass data. The symbols "*", "+" and "!" correspond to logical AND, OR and NOT, respectively.

Mass Setting	Number	Prescale	Requirements
high	PhysB1	800	X134L * X134R
	PhysB2	1000	(MUL + MDL + MUR + MDR)
	PhysB3	-	-
	PhysB4	-	-

2.7 Data Acquisition System

The E866 data acquisition system (DAQ) was essentially an upgraded version of the system used in E789. The DAQ had three areas of responsibility: event readout, data archiving and online analysis. The backbone of the event readout was the Nevis Transport System. Upon receipt of a signal from one of the Track Correlators, a busy signal was raised which inhibited further triggers from being accepted. Simultaneously, the first word of the event was inserted onto the transport bus. Signals were sent to the TDC readouts on the drift chambers and the coincidence registers (CR's) on the hodoscopes. When signaled, the TDC's and CR's began digitizing their signals for insertion onto the bus. Each hodoscope and proportional-tube hit resulted in the insertion of an identifying word on the bus. The TDC's would also start a timer which would be terminated by the amplified signal from the drift chamber. This provided a measurement of the drift time in the chamber, which was inserted onto the transport bus along with the number of the struck wire.

At this point, the data stream on the transport bus was fed into the Versa Module Eurocard (VME) based archiving system. During the 20s spill cycle, data were first transported to a pair of high-speed memory boards. Once one of the boards was full, it was drained into a large memory buffer while the other board was filled. Upon completion of the spill, the data were then formatted and sent down the VME pipeline to the tape archiving system. Here the data were written out to 8mm Exabyte tapes. Additionally, a fraction of the event data and all of the spill information (number of triggers fired, SEM counts, target position, etc...) were sent to the online monitoring systems.

The online monitoring system consisted of a database system interfaced to several graphical tools, and the E866 online analysis code. The database system allowed us to monitor the status of various components of the beamline and spectrometer. Graphical displays of the luminosity, magnet voltages, livetimes, etc..., gave an overall indication of the health of the spectrometer. The online analysis code analyzed the data that were sent to it via the VME pipeline. The histograms generated by the analysis code were accessible in real time by making use of PAW (Physics Analysis Workstation) [PAW] global sections. This allowed us to monitor the detector planes, watching for and correcting any inefficiencies which might develop.