Fermi National Accelerator Laboratory

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# A STUDY OF THE TRANSPORT OF HIGH ENERGY MUONS THROUGH A SOIL SHIELD AT THE TEVATRON

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ABSTRACT

The transport of high energy muons in a soil shield was studied by making fluence distribution measurements at three different locations following a 600 meter thick earth shield. The incident muon beam had a broad momentum spectrum with a mean of about 500 GeV/c. The results are compared with Monte-Carlo calculations of muon transport. Agreement between calculations and measurements is generally excellent when the muon beam was incident directly on the earth shield. In another series of measurements, the muons were magnetically deflected downward before impinging on the shield. This greatly reduced the muon fluence at distant locations and somewhat worsened the agreement between the model calculations and the observations, most likely by increasing the relative importance of sources of muons not included in the model. Still, peak values in muon fluence distributions are adequately described by the calculations.

*Operated by Universities Research Association under contract with the U. S. Department of Energy

## 1. Introduction

The subject of muon production and transport at high energy proton accelerators has been of interest since initial work in the 300 GeV range by Keefe and Noble [1]. Much work was done at Fermilab by Theriot and Awschalom [2], Van Ginneken [3], and later by Mori [4]. Other theoretical work has been reported by Maslov, Mokhov, and Uzunian [5]. Results of these studies have been used both for protection against environmental radiation and in the reduction of experimental backgrounds. A number of methods of calculation have been used; most invoke some form of the Monte-Carlo technique. Until now the highest momentum at which measurements of muon transport were done was 280 GeV/c in a study at CERN reported by Nelson, et.al. [6], where experimental fluence was compared to calculations for muons transported in a 300 meters thick earth shield.

At low energies, the energy loss of muons, and thus, their transport through matter is dominated by atomic ionization and excitation. At momenta greater than ≈ 100 GeV/c, however, the processes of bremsstrahlung, pair production, and nuclear interactions (basically inelastic scattering) become more important sources of energy loss. Recently, Van Ginneken [7] has reported a detailed study of energy loss and angular distributions of high energy electromagnetic processes (which bears directly on the transport of muons) for energies up to 30 TeV. The results have been incorporated into the Monte-Carlo program CASIM [8], and used by Van Ginneken, Yurista, and Yamaguchi to study the production and transport of both hadrons and muons in thick shields for energies up to 20 TeV [9]. Dramatic departures from the simple low energy picture dominated by collisional energy losses and multiple Coulomb scattering are found. Since muon production mechanisms have uncertainties of their own it is desirable to perform measurements under conditions where transport can be decoupled from production. The initial operation of the Tevatron Muon Beam [10] provided a unique opportunity for studying muon transport for a beam of incident muons spanning the momentum region of 200 to 700 GeV/c. The present report describes such measurements; the results are compared to calculations using the updated version of the code CASIM [9].

## 2. Experimental Conditions

The Tevatron Muon Beam has been described in considerable detail by Malensek and Morfín [10] so that only a brief summary will be provided here. Protons incident on an aluminum target in an underground beam enclosure are used to produce a broad spectrum of hadrons at a distance of approximately 1.7 kilometers upstream of the experimental hall. These hadrons and their decay products, including positively-charged muons, are collimated and focussed into a beam suitable for transport by a focussing-defocussing series of quadrupole magnets (FODO) optimized to transport a broad spectrum beam to the physics experiment. The first 1.1 kilometers of the FODO is used as a decay region for the parent pions and kaons. This region is terminated with a beryllium absorber which removes essentially all of the remaining hadrons. The remainder of the FODO is used to transport a nearly pure beam of muons. Since the objective is to obtain a well-collimated and momentum-analyzed beam of muons, both a large toroid and a magnetized iron pipe surrounding the beam are used to deflect undesired muons away from the beam axis. Both design studies and beam commissioning measurements indicate that these magnetic elements are effective in removing the unwanted "halo" from the muon beam. The halo contamination remaining within the quadrupole apertures beyond these devices is only a few percent of the muon beam.

After transport through the FODO, the beam muons are focussed on a target in the experimental hall where their interactions are studied. By design, the size and shape of the beam, its divergence, and its momentum spectrum are readily measured by the physics experiment. The mean momentum of the muon beam produced by 800 GeV protons presently available from the Tevatron is tuneable over a fairly large range, but results described here all refer to an operating mode which produces a broad spectrum centered upon a momentum of about 500 GeV/c. The ratio of the intensity of the muon beam as measured with a scintillation counter telescope to that of the incident proton beam as measured with a secondary emission monitor (SEM) is approximately $10^{-5}$. This yield is quite stable as a function of time. At the experimental hall the muon "halo" and the "beam" are, according to calculations, of similar total intensity but the halo is dispersed over a much larger area and concentrated in two peaks-one below and the other to the east of the beam (which is directed to the NNE compass direction) [11].

Following the high energy physics experiment, the muons continue through the air in the underground experimental hall and finally enter an earth shield. While in the experimental hall the beam of muons is approximately 2.4 meters above the floor. Beyond the experimental hall, the elevation of the surface of the ground above the beam as a function of longitudinal coordinate, Z, is shown in Fig. 1. The origin is at the beginning of the earth shield; positive Z measures distance along the extension of the beamline into the earth shield, positive Y measures distance above the beamline, and the direction of the positive X-axis is defined by the right hand rule and is roughly to the WNW in terms of compass direction. The measurements of the terrain for the region $0 < Z < 1000$ meters were determined by optical survey while those for $Z > 1000$ meters were taken from United States Geological Survey maps.

The soil at Fermilab is typically a heavy clay. Its density has been measured in numerous places, including near the facility being discussed here. An appropriate value is 2.25 g $cm^{-3}$. Beyond the experimental hall, however, the land has been cultivated for many years and the top approximately 30 cm should have a lower density; 1.4 g $cm^{-3}$ is a reasonable estimate.

## 3. Measurement Techniques

Muon fluence was measured using the Fermilab Mobile Environmental Radiation Laboratory (MERL) [12]. The detector consisted of a pair of 0.64 cm thick plastic scintillation counters with transverse dimensions of 20.32 cm by 20.32 cm and separated by 15 cm. A 2.54 cm thick aluminum plate was inserted between the two counters to reduce possible false coincidences due to $\delta$-rays. These counters were mounted in a vehicle at a height of 1.2 meters above the ground and were oriented so that the muons were approximately at normal incidence. Standard electronic modules were used to record on scalers both singles and coincident events. One set of scalers was gated "on" during the beam spill (23 sec long, repeated approximately once per minute) and a second set was gated "on" during a period of similar length between spills to obtain a background measurement. A microwave telemetry system provided synchronization with the accelerator cycle and transmission of SEM data to allow normalization to the incident proton beam intensity.

Two scintillator paddles operated in coincidence serve to distinguish muons from other radiation, and, where the fluence is small, provide a more sensitive measure of their presence than do the singles rates from either paddle. However, under conditions in which there are no other components of the radiation field for which the plastic scintillator has a finite efficiency, the singles rate provides a better measure of muon flux. This is because the coincidence rate depends upon the direction and divergence of the incident beam. For a broad, parallel beam incident normal to the scintillators, the ratio of coincidence-to-singles-rates should be close to unity. For a non-parallel beam, or one that is not incident normally, the ratio will be less than one and can vary depending on the divergence in the muon trajectories. Neutrons are a potential source that could affect the counting rates. Each plastic scintillator has an intrinsic efficiency of approximately 7.5 % for neutrons of a few MeV. A separate neutron detector determined that the neutron contribution to the radiation field was negligible for the measurements reported here. Also, the coincidence-to-singles ratio was 0.8 to 0.85 at the peak of the fluence distribution for many of the results reported here. Thus, singles rates in the scintillation counters were used to determine the muon fluence.

The measurements were made at three locations denoted by the filled symbols in Fig. 1. At each of these locations, one or more scans in the X (horizontal) coordinate were made. Detector counts were recorded for at least two beam spills at each point (X,Y,Z) along an individual scan. Measurements were performed both nearly centered on the extension of the beam axis (at Z = 1000 meters) and also in the "fringes" ( at Z = 1640 meters and Z = 2036 meters). Proper operation of the detectors (i.e., high voltage and amplifier gain adjustments, discriminator thresholds, coincidence timing, and gating) was insured by first setting up in a known muon field at another location on the Fermilab site. The fluence in that field was sufficient to give a high statistics pulse-height spectrum of the nearly minimum-ionizing muons, making detector setup straightforward.

## 4. Model and Calculations

Because the earth shield and the muon production target are separated from each other by a long distance, the transport of the "beam" muons in the soil shield is rather completely decoupled from the production mechanisms. The muon transport portion of a recent version of the Monte-Carlo program CASIM by Van Ginneken, et.al. [9], incorporating the physical mechanisms described in Ref. 7, was used to model the conditions described above. The code was modified to bypass the hadronic cascade portion and proceed directly to the muon transport section. Incident muons were "created" in the Monte-Carlo calculation at a distance of 27 meters upstream of the beginning of the soil shield. The beam spot at this location was modeled as a bigaussian, with standard deviations $\sigma_X = \sigma_Y = 6.5$ cm. Beam divergence was taken into account in an approximate way by selecting divergence angles of the muons with respect to the Z-axis that were proportional to their transverse coordinates (e.g., $\theta_X = aX/\sigma_X$ and $\theta_Y = bY/\sigma_Y$ milliradians). The fluence results were only weakly sensitive to the choice of a and b, varying by about 10 % for $0.3 < a,b < 0.5$. Values of a and b equal to 0.4 were used for the results reported in this paper.

Figure 2 shows a measurement of the incident muon spectrum (open symbols) as determined by the physics experiment using their magnetic spectrometer system [13]. These data were used as the basis for a distribution function from which the momenta of the incident muons were taken in the Monte-Carlo calculations. The solid line superimposed on the measurements in Fig. 2 simply illustrates the expected excellent agreement between a typical Monte-Carlo generated spectrum of incident muons and the measured spectrum. It is important to note that the measured spectrum (and likewise the Monte-Carlo calculation) only includes "beam" muons above a momentum threshold of 200 GeV/c.

After their "creation" in the calculations, the incident muons passed to the downstream wall of the experimental hall (Z = 0) where they entered the earth shield. Throughout the calculations, the air in the experimental hall and above the soil surface was explicitly included. Upon entry into the soil shield, the muons were followed through it, using a data table to determine if the muon was in the dense soil, the cultivated layer, or the air above the soil. The soil densities given in section 2 were used in the calculations reported here. The results were fairly sensitive to the choice of density; for example a 10 % lower choice for the uncultivated soil density (2.0 g $cm^{-3}$) leads to predicted fluences 50 % larger at the locations of the measurements.

Modifications to the original program of Van Ginneken et.al. [9] were made to allow selection of specific Z-values to correspond with the locations of the measurements. At each value of Z so chosen, a table of muon fluence was generated as a function of X and Y. The bins were, in all cases, 200 cm by 200 cm. The tabulated values were then compared to the measurements. In nearly all cases, this bin size was sufficiently large to allow collection of statistically meaningful results while still small enough to be able to see any structure in the distribution. In order to conserve computer time, a variable step size was used. This parameter is the distance traveled by the hypothetical muon between calculations of the effects of its interaction with matter. A step length of 100 cm was used for $-27 < Z < 1$ meters while a value of 40 meters was chosen for $Z > 1$ meter. The results were not sensitive to the latter rather large choice. To follow $7 \times 10^4$ incident muons a computer run required approximately 2200 s of CYBER-875 equivalent CPU time. Two different choices of the initial values for the random number generator were tried; the results were quite insensitive to this selection. No "artificial" normalizations were applied to any of these calculations or measurements; the comparisons are on an absolute basis.

## 5. Results and Discussion

### A. Direct Incidence of Muons on the Soil Shield

The distributions of muon fluence measured at Z = 1000 meters, 1640 meters, and 2036 meters are compared with the results of the Monte-Carlo calculations in Figs. 3, 4, and 5. In all cases the values are in units of $cm^{-2}$ per $10^{12}$ incident protons. For the measurements, the normalizations were made to the proton intensities recorded by the beamline SEM. Typical intensities were 1 to 4 X $10^{12}$ protons per beam spill. The output of the calculations was initially normalized to the incident muon intensity. These values were then multiplied by the measured yield of $10^{-5}$ muons per incident proton for comparison with the measurements. In the figures, error bars are based only on counting statistics with beam-off (background) counting rates subtracted. In most cases the error bars are smaller than symbols used to represent the data points.

At Z = 1000 meters the agreement between measurements and calculations is excellent for both the magnitude and width of the fluence distribution, as seen in Fig. 3. At this location the scintillation counters are nearly at the same elevation as the beam, and over 60 % of the muon trajectory is in earth.

Due to the increased elevation at Z = 1640 meters, the measurement location is at an angle of approximately 1.8 milliradian to the beam axis so that a large part of the muon trajectories are in air. Most muons probably traverse no more earth than those measured at Z = 1000 meters, although a small fraction that arrive at this location are scattered from the nearby earth. The MERL detectors were about 3.4 meters above the beam elevation at this location. As seen in Fig. 4, the calculated results are 80 % of the measurements at the peak of the fluence distribution; the calculated full-width at half-maximum (FWHM) is slightly smaller than the measured one.

At the location Z = 2036 meters, the MERL scintillation counters were located at an angle of approximately 2.4 milliradians relative to the beam axis, and were at an elevation of 4.6 meters above it. Again, as at Z = 1640 meters, most muons arrive having traversed more air than earth. Even so, as seen in Fig. 5, the measurements are only 1.4 times larger than the calculations at the peak. The FWHM of the measured distribution is 18 meters and the ratios of coincidence to singles counting rates in the detectors is about 0.85 near the peak of the distributions, both of which suggest that the muons remain in a well-collimated beam even after penetrating 2 kilometers of earth and air.

Note that there is an increasing discrepancy between the calculations and the measurements in the tails of the distributions where the measured distributions generally "level off" near a value of approximately 0.1 $cm^{-2}$ per $10^{12}$ protons. In the calculations, it should be recalled, the source muons were "created" a few meters upstream of the earth shield. In the actual experimental conditions, however, the muon beam arrives at the soil shield surrounded by a "halo" of other muons not totally eliminated by upstream beamline components. In addition, muons that arise in the proton beam dump far upstream (which are subject to far different transport and shielding conditions than are those in the "useful" beam) may also reach the earth shield under study here. Other Fermilab beamlines, synchronized with the accelerator cycle and originating within $10^{o}$ of the same general direction as the muon beam, were also in operation during the measurements reported here and could contribute to a beam-on muon background. All measurements were made "parasitic" to the operation of the high energy physics program; observations with only one beamline in operation were, in general, not made. For these reasons, it is not too surprising that the agreement between calculations and measurements in the tails of the fluence distributions is relatively poor.

**B. Deflected Muons Incident on the Soil Shield**

The location at Z = 2036 meters is essentially at the Fermilab site boundary. The measured peak muon fluence (Fig. 5) corresponds to a dose equivalent of 1.1 nSv for $10^{12}$ incident protons using a conversion factor of 40 fSv-$m^2$ which is appropriate for a large range of muon energies, as shown by Stevenson [14]. Multiplication by the number of protons targeted in this beamline during 1987 results in an offsite dose equivalent of 0.13 mSv, 30 % higher than the Fermilab goal to limit such exposures to 0.1 mSv annually.

In order to reduce the fluence offsite, two specially-built magnets were installed in the beamline downstream of the physics experiment to deflect the muons downward before they entered the earth. These toroidal "spoilers" and their positions relative to the beam are shown in Fig. 6. Measurement of the excitation of the resulting toroidal magnetic field determined the magnetic length of each magnet to be approximately 3.05 meters at a field of 1.5 T [15]. Thus the total field integral for the two magnets was approximately 9.1 T-m and represented a transverse momentum "kick" of 2.75 GeV/c. These magnets were placed parallel to the muon beam but were offset so that the beam hit the most upstream lamination halfway between the center and the lower edge. The two toroids therefore functioned essentially as dipoles with respect to the muon beam.

With these magnets in place, the distribution of muon fluence was measured at the same locations as above, and the results compared to the CASIM transport calculations. For these calculations, the incident muons were "created" at the upstream face of the first toroid; the beam properties were the same as discussed in section 4. The effective density of the magnet iron was assumed to be 7.0 g $cm^{-3}$, smaller than normal because of the existence of gaps between the laminations. The results of the calculations are only weakly sensitive to this choice of density. For these magnets, the magnetic field was modeled to be that of an ideal toroid appropriately offset as shown in Fig. 6 with a magnetic field throughout the iron set to yield the estimated field integral. The calculations neglected any fringe fields of the toroids.

The results at Z = 1000 meters are shown in Fig. 7. The measured peak muon fluence was reduced by a factor of 20 and the width of the distribution broadened relative to the case where no toroid was present. Also the center of the muon beam (at the average momentum of $\approx$ 500 GeV/c) is calculated to be about 6 meters below the MERL detectors because of the downward magnetic deflection. Even so, agreement between calculations and measurements is excellent in both peak fluence and width. Deviations only occur in the tails of the distribution where, as discussed previously, muons from other sources may be more significant.

A separate calculation was performed using CASIM to transport the "halo" muons through the earth and air shield in order to investigate their importance compared to the "beam" muons. These "halo" muons were "created" in the model just upstream of the first toroid using an "incident" distribution in position and momentum taken from calculations made by Malensek [11]. This distribution is such that only a few of these muons actually are affected by the toroids. As seen in Fig. 7, the shape of the calculated distribution after transport is not an adequate representation of the observations in the tails although the magnitude to the East (X < 0) side of the peak is in qualitative agreement.

At the two most distant locations the peak fluences are reduced by factors of 18 (Z = 1640 meters) and 15 (Z = 2036 meters) below the no-toroid values. Detector elevations are 12.2 meters (Z = 1640 meters) and 15.9 meters (Z = 2036 meters) above the deflected beam elevations (for 500 GeV/c muons). Even so, the calculations provide a reasonable estimate of the maximum value of the fluence, as seen in Figs. 8 and 9. The measured shapes of the distributions, on the other hand, are so broad as to hardly resemble peaks at all and are not predicted by the model. Repeat measurements made on different days when, ostensibly, the beamline and high energy physics experiment were operated under the same conditions, show differences particularly in the region to the west (X > 0) of the "beam". This lack of reproducibility probably reflects the fact that at very low intensity levels the muon field may be dominated by contributions from adjacent independently-operated beamlines. The most prominent of such sources would appear to the west (X > 0) of the beam under study. It is clear, as seen in Figs. 8 and 9, that the "halo" contributions to the fluence are too small to adequately explain the background level observed to the west of the beam. To the east, there is some suggestion that the "halo" contribution may be significant.

## 6. Summary

The transport portion of the recently modified CASIM Monte-Carlo computer program accurately represents measured fluence distributions for muons even after they travel through 2000 meters of earth and air. This is particularly true for incident muons in a well-collimated beam. But even in the case of magnetic beam deflection before the particles impinge on the earth shield (a configuration designed to drastically reduce the muon fluence at distant locations) the maximum values of the fluence are fairly estimated in the calculations. Since the muon intensity has been reduced almost to background values, the actual shape of the observed distributions at these distant locations depends rather critically on contributions to the muon field not included in the model calculation. Given the various uncertainties, it is concluded that the data is explained quite successfully by these calculations.

Future measurements at different elevations are planned in order to study the Y-dependence predicted by CASIM.

## 6. Acknowledgement

We would like to thank J. Morfín and A. Malensek for their helpful discussions of the operation of the beam, and J. Larson and T. Anderson for maintaining reliable operation of the apparatus. Special thanks are due to A. Van Ginneken for making the program CASIM available to us and for many helpful discussions and suggestions concerning the content of this report.

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**List of Figure Captions**

1. Distance of the surface of the earth above the beam as a function of longitudinal coordinate Z. The origin is defined to be at the downstream end of the experimental hall. The filled symbols are plotted at locations where scans in the X-coordinate were made.

2. Measured momentum distribution (open symbols) of incident muons plotted as probability per GeV/c. Both linear and semi-logarithmic plots are given. The solid line is a "playback" of the distribution used in the Monte-Carlo calculation to verify that the correct distribution function was being applied.

3. Muon fluence measurements and calculations at Z = 1000 meters, Y = 0.45 meters for the muon beam directly incident on the earth shield. The units of muon fluence are $cm^{-2}$ per $10^{12}$ incident protons. Both linear and semi-logarithmic plots are given.

4. Muon fluence measurements and calculations at Z = 1640 meters, Y = 3.35 meters for the muon beam directly incident on the earth shield. The units of muon fluence are $cm^{-2}$ per $10^{12}$ incident protons. Both linear and semi-logarithmic plots are given.

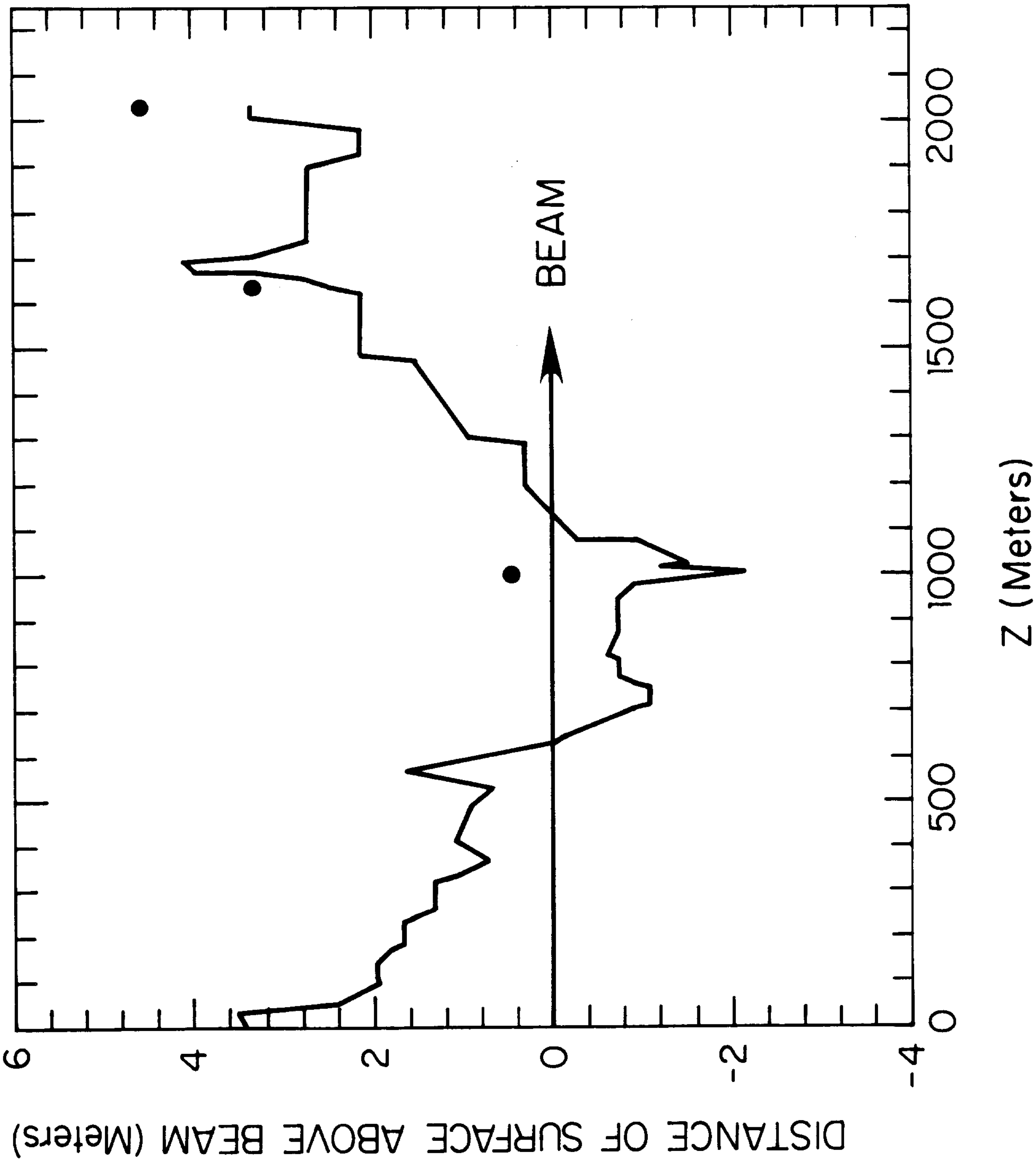
5. Muon fluence measurements and calculations at Z = 2036 meters, Y = 4.57 meters for the muon beam directly incident on the earth shield. The units of muon fluence are $cm^{-2}$ per $10^{12}$ incident protons. Both linear and semi-logarithmic plots are given.

6. Location with respect to the incident muon beam of the "spoiler magnets" with a toroidal magnetic field used to deflect postiively-charged muons downward. The right hand coordinate system is also shown.

7. Muon fluence measurements and calculations at Z = 1000 meters, Y = 0.45 meters for the deflected muon beam incident on the earth shield. The units of muon fluence are $cm^{-2}$ per $10^{12}$ incident protons. Also shown is the calculated contribution of the "halo" muons. Both linear and semi-logarithmic plots are given.

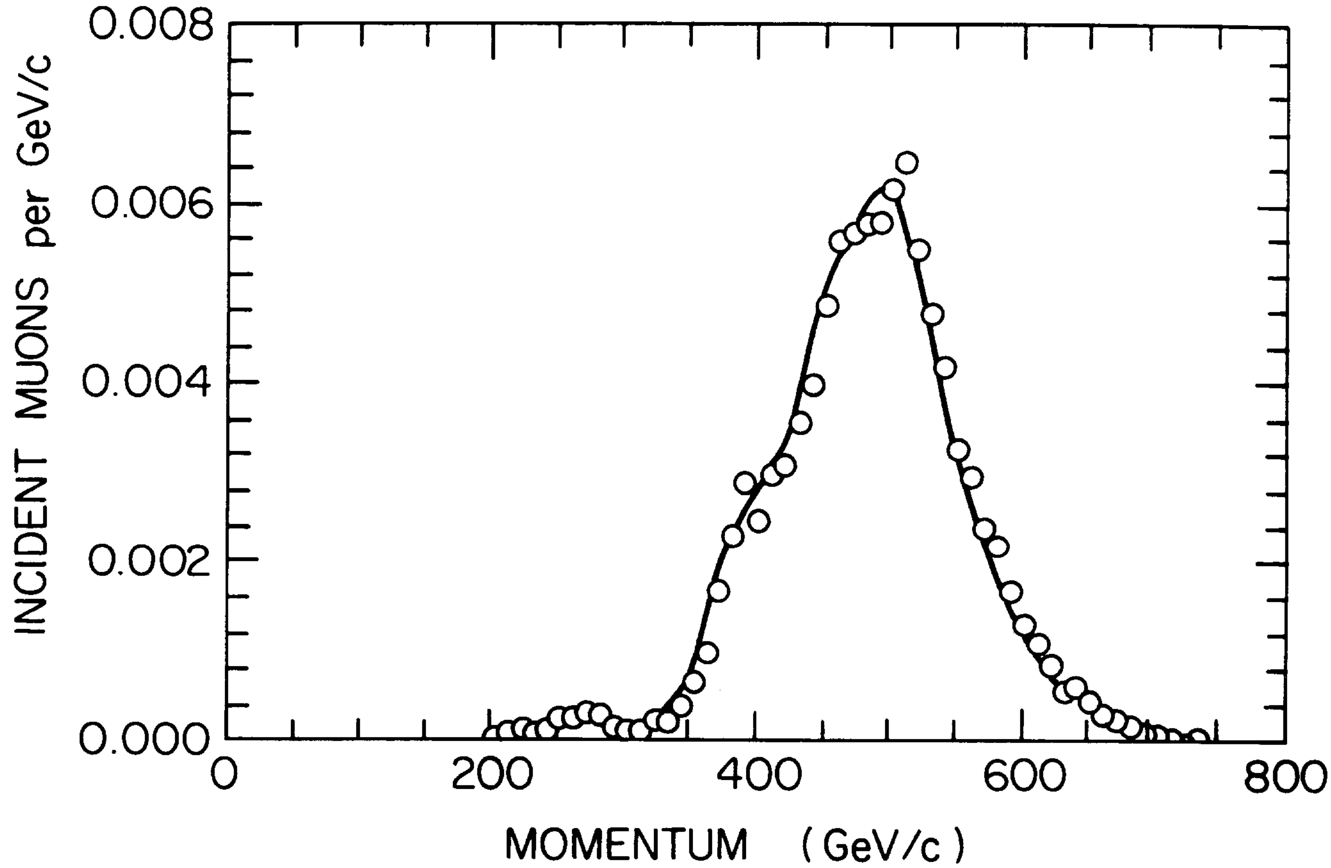
8. Muon fluence measurements and calculations at Z = 1640 meters, Y = 3.35 meters for the deflected muon beam incident on the earth shield. The units of muon fluence are $cm^{-2}$ per $10^{12}$ incident protons. Also shown is the calculated contribution of the "halo" muons. Both linear and semi-logarithmic plots are given. The measurements were made on more than one occasion. The occasions are denoted "Data Day 1", etc.

9. Muon fluence measurements and calculations at Z = 2036 meters, Y = 4.57 meters for the deflected muon beam incident on the earth shield. The units of muon fluence are $cm^{-2}$ per $10^{12}$ incident protons. Also shown is the calculated contribution of the "halo" muons. Both linear and semi-logarithmic plots are given. The measurements were made on more than one occasion. The occasions are denoted "Data Day 1", etc.



DISTANCE OF SURFACE ABOVE BEAM (Meters)
6
4
2
0
-2
-4
Z (Meters)
0
500
1000
1500
2000
BEAM


Figure 1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0.004
0.002
0.000
0
200
400
600
800
MOMENTUM (GeV/c)

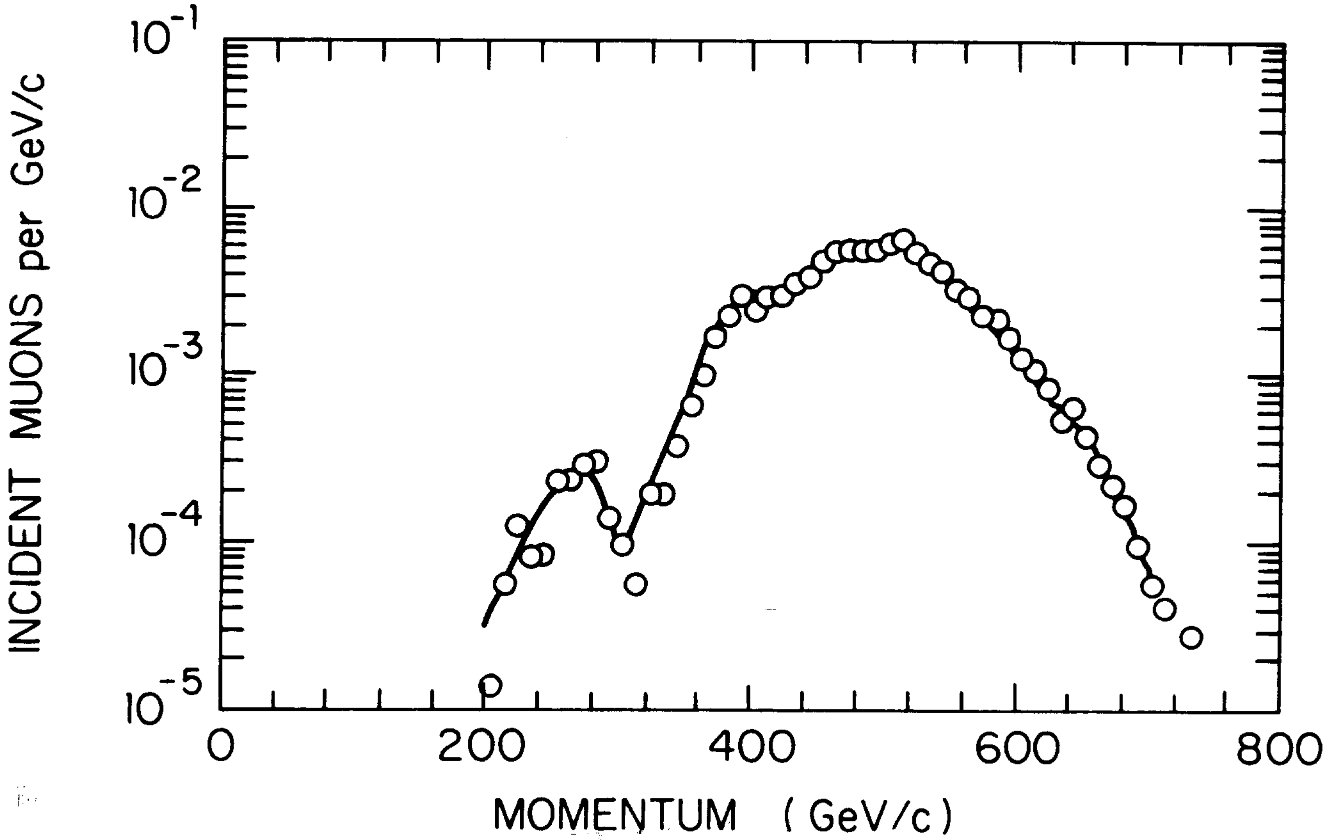
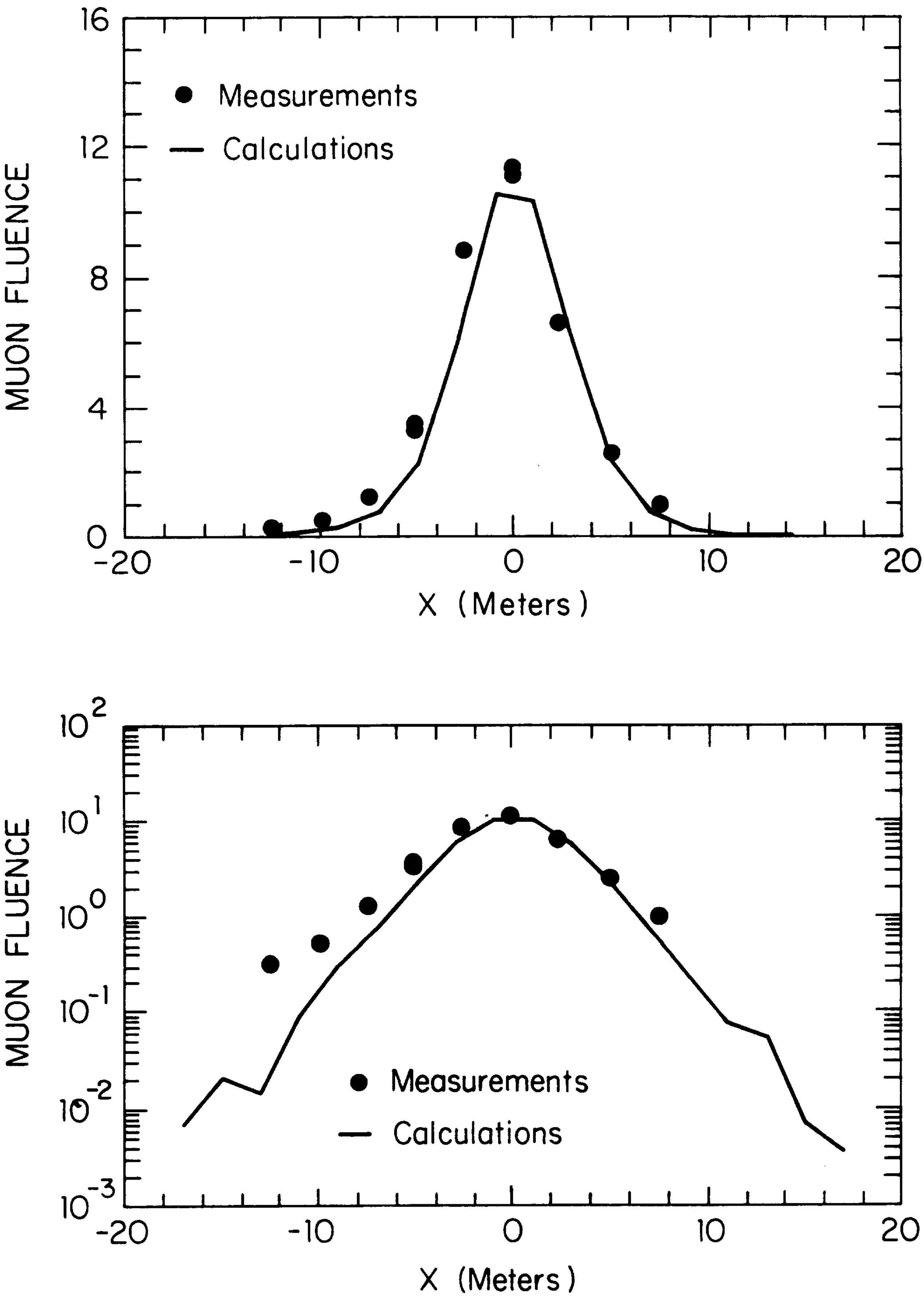
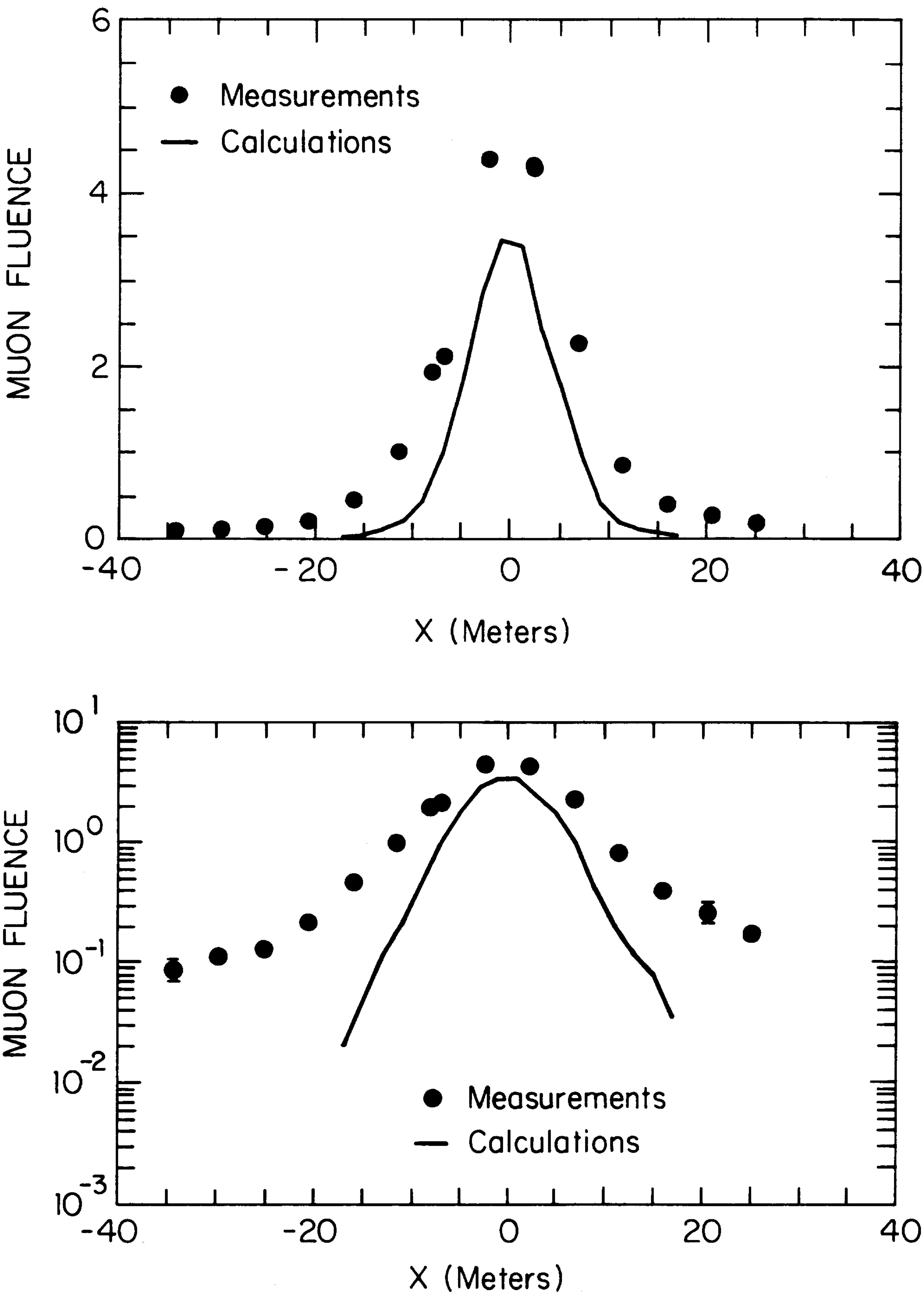

INCIDENT MUONS per GeV/c
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
0
200
400
600
800
MOMENTUM (GeV/c)

Figure 2



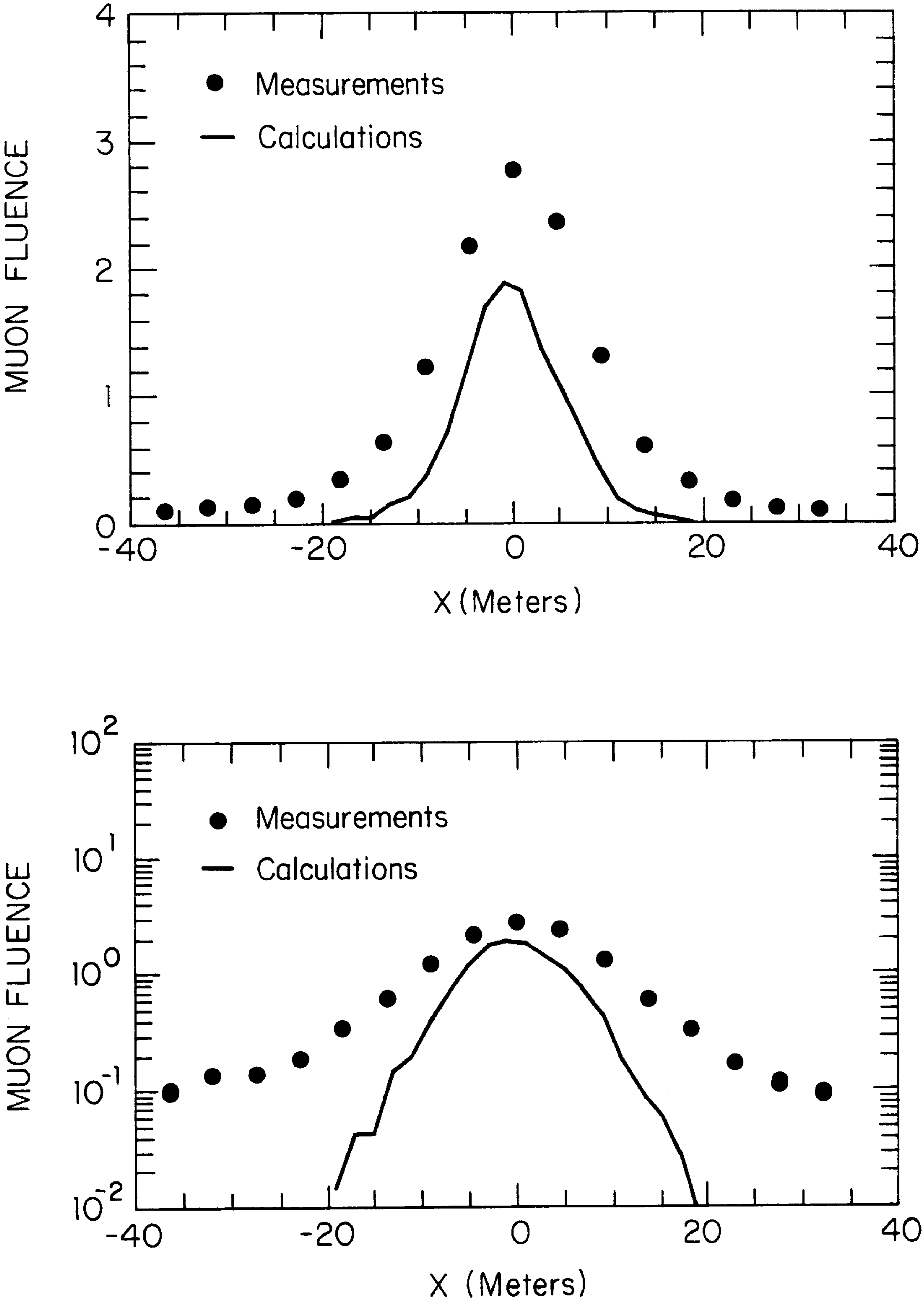
Measurements
Calculations
MUON FLUENCE
16
12
8
4
0
-20
-10
0
10
20
X (Meters)
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
MUON FLUENCE
Measurements
Calculations
-20
-10
0
10
20
X (Meters)

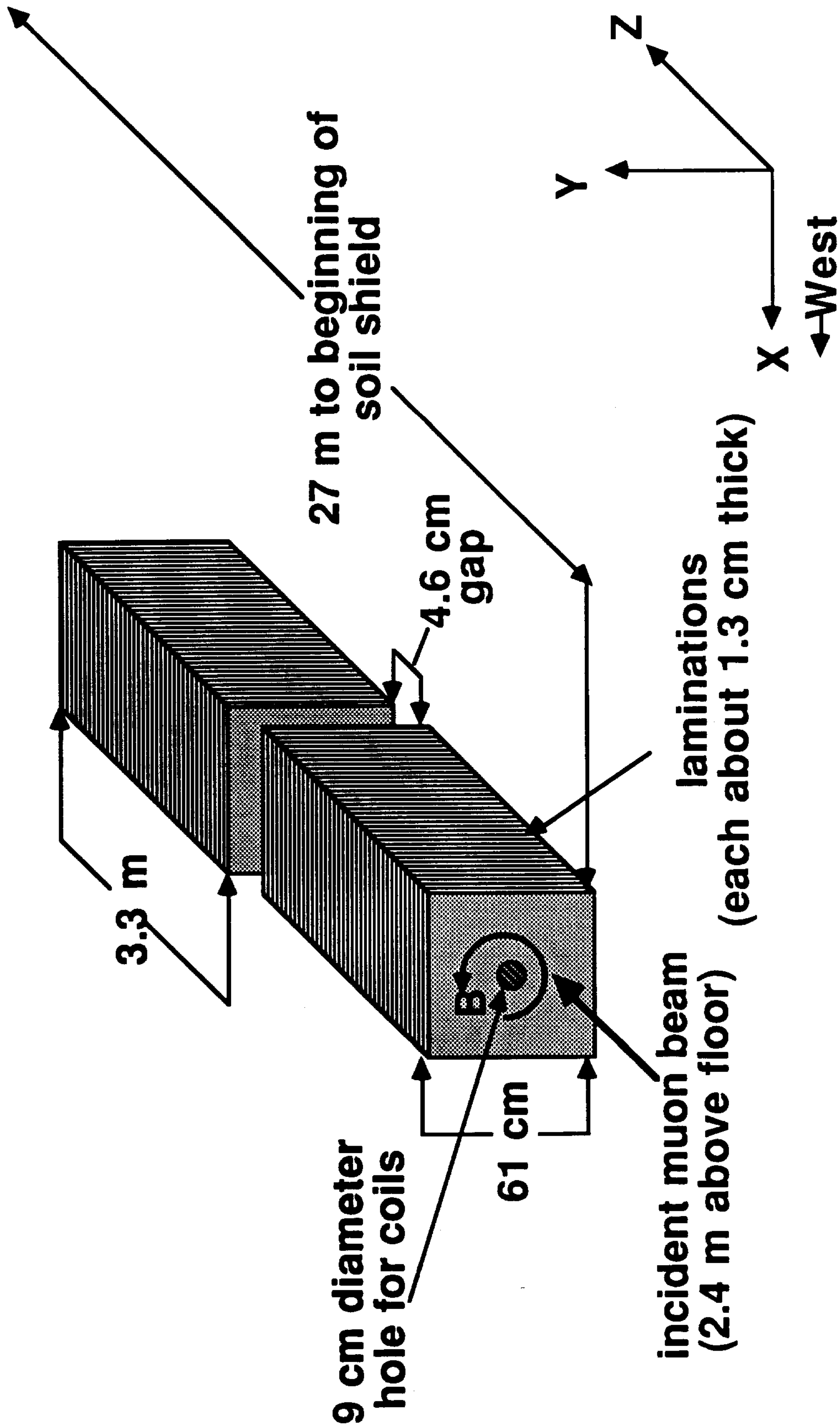

Figure 3



MUON FLUENCE
Measurements
Calculations
X (Meters)
MUON FLUENCE
Measurements
Calculations
X (Meters)

Figure 4


Measurements
Calculations
MUON FLUENCE
X (Meters)
Measurements
Calculations
MUON FLUENCE
X (Meters)
Figure 5



27 m to beginning of soil shield
Z
Y
X
West
4.6 cm gap
3.3 m
laminations (each about 1.3 cm thick)
B
61 cm
9 cm diameter hole for coils
incident muon beam (2.4 m above floor)


Figure 6

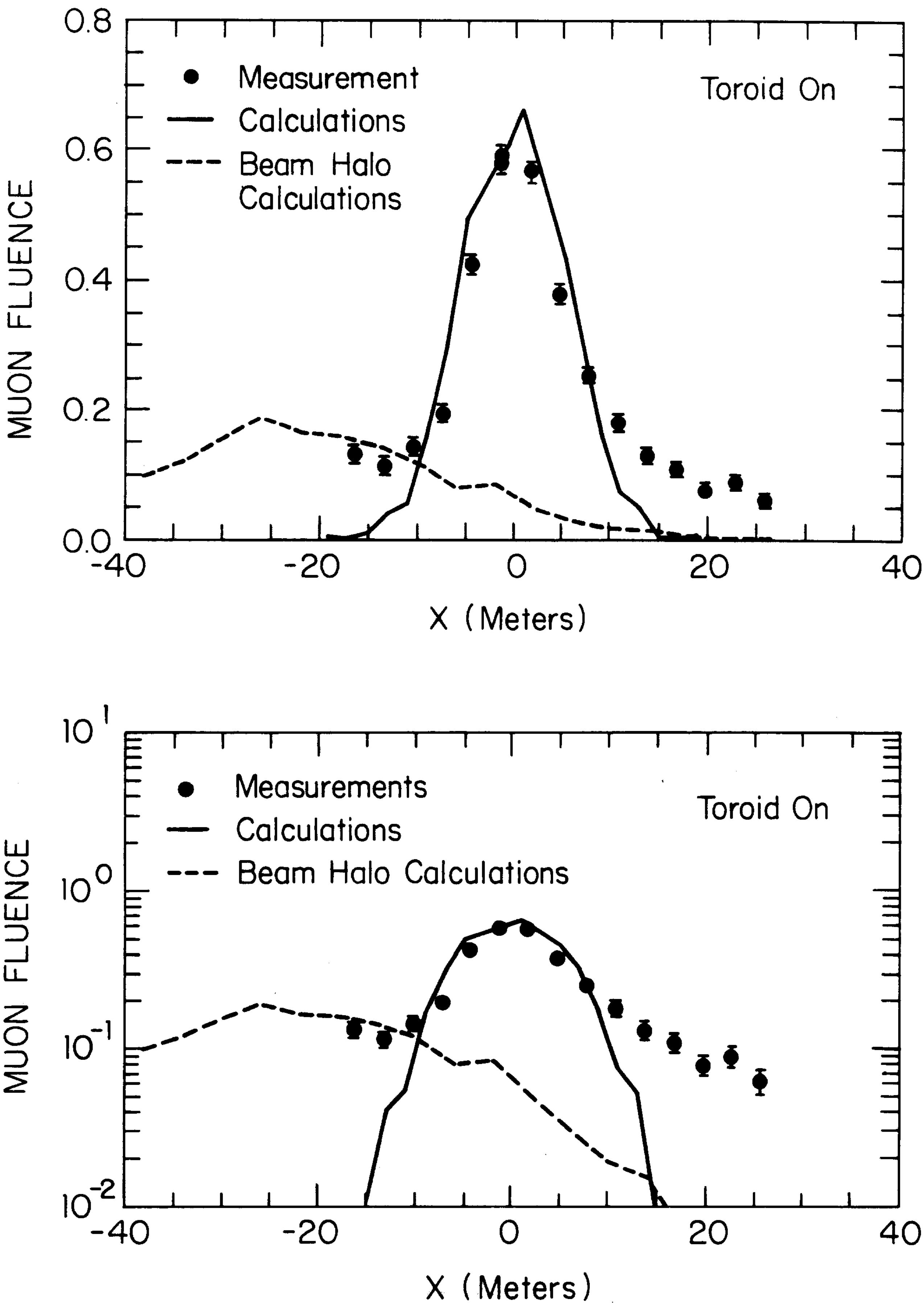
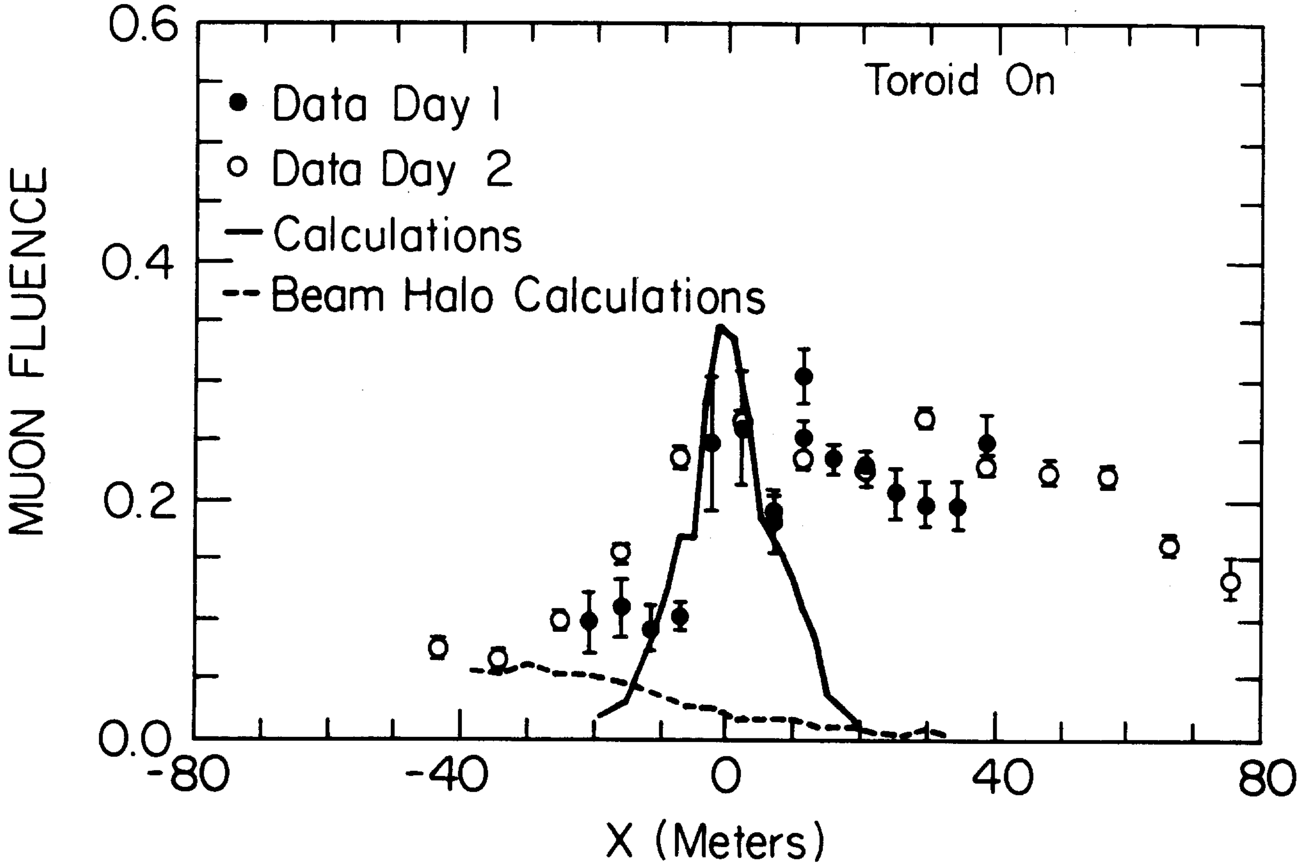
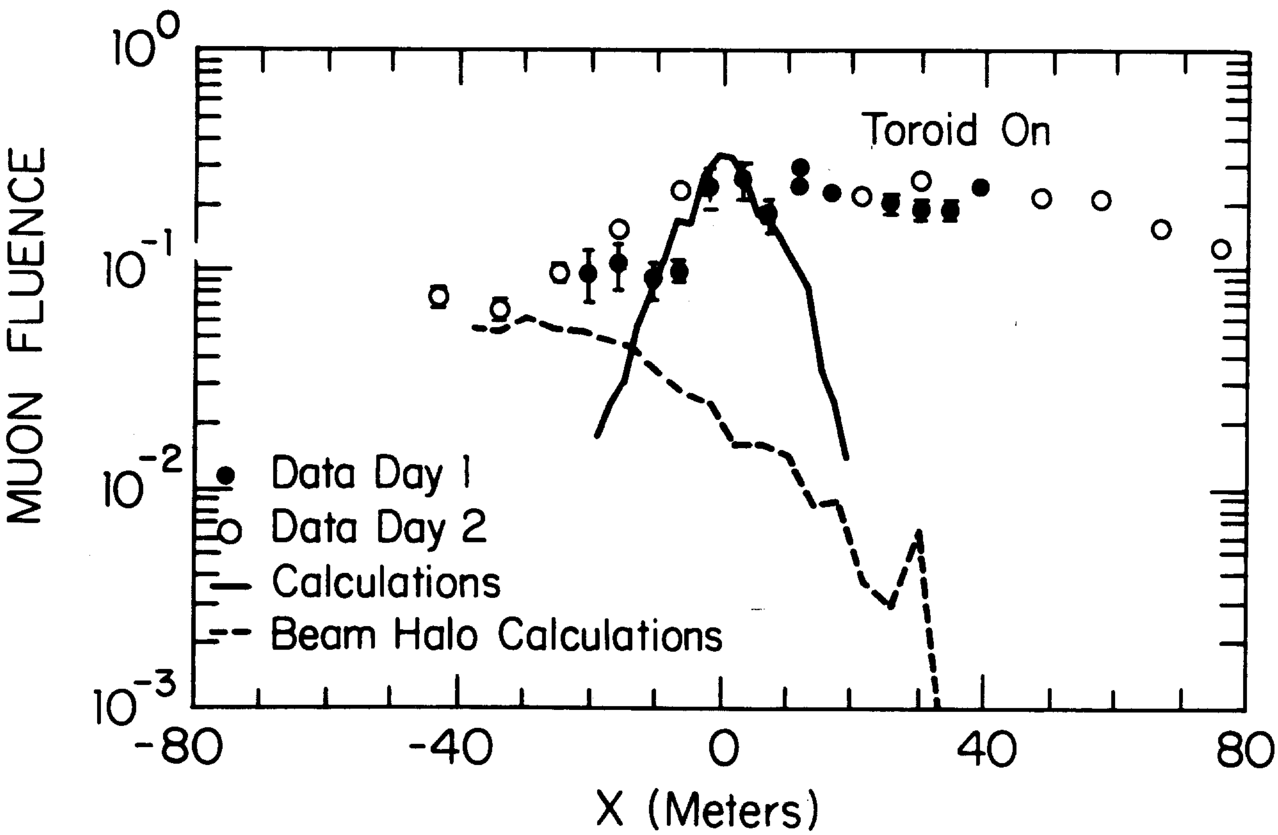

0.8
0.6
0.4
0.2
0.0
Measurement
Calculations
Beam Halo
Calculations
Toroid On
MUON FLUENCE
-40
-20
0
20
40
X (Meters)
10^1
10^0
10^-1
10^-2
Measurements
Calculations
Beam Halo Calculations
Toroid On
MUON FLUENCE
-40
-20
0
20
40
X (Meters)

Figure 7



0.6
0.4
0.2
0.0
MUON FLUENCE
Toroid On
Data Day 1
Data Day 2
Calculations
Beam Halo Calculations
-80
-40
0
40
80
X (Meters)

$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
MUON FLUENCE
Toroid On
Data Day 1
Data Day 2
Calculations
Beam Halo Calculations
-80
-40
0
40
80
X (Meters)


Figure 8

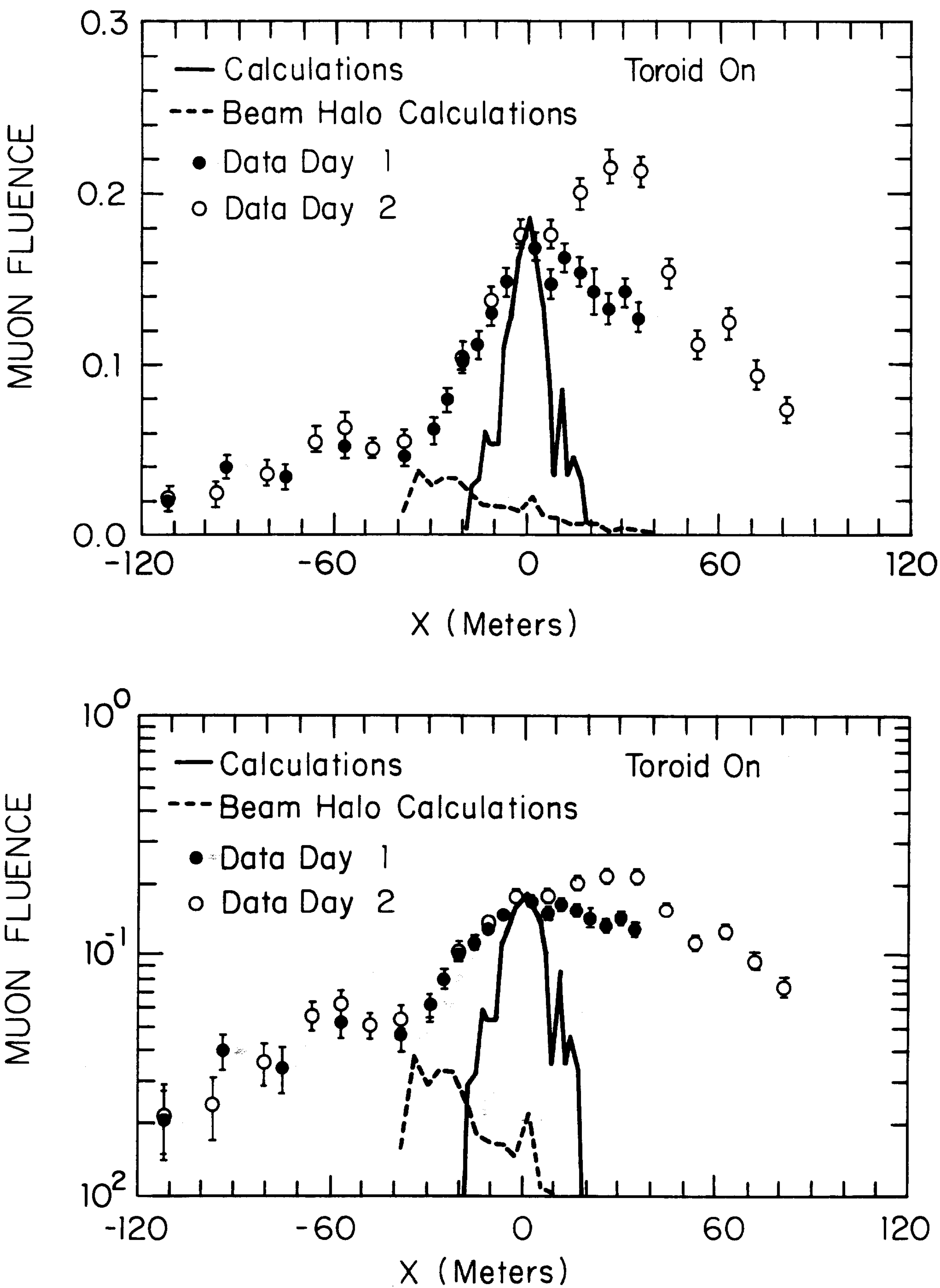

MUON FLUENCE
0.3
0.2
0.1
0.0
Calculations
Beam Halo Calculations
Data Day 1
Data Day 2
Toroid On
-120
-60
0
60
120
X (Meters)
MUON FLUENCE
10^0
10^-1
10^2
Calculations
Beam Halo Calculations
Data Day 1
Data Day 2
Toroid On
-120
-60
0
60
120
X (Meters)

Figure 9