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Recent Muon Dose Equivalent Measurements at Fermilab

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Muon radiation fields at Fermilab were measured during 1980-1981 using the Mobile Environmental Radiation Laboratory (MERL). Measurements were made during the spring of 1980 with the accelerator operating at 350 GeV and during the spring of 1981 with the accelerator operating at 400 GeV. The goal of the measurements was to obtain an understanding of muon dose equivalent rates at various locations on the Fermilab site, particularly at those locations useful in determining the off-site contribution of accelerator produced muons to the radiation exposure of the general off-site population. In the course of these measurements, all primary beam lines were studied at least at one of the two energies and several were studied at both energies in an attempt to examine the energy dependence of these radiation fields.

1. Experimental Technique

The MERL contains a pair of plastic scintillator paddles each 20.32 cm square by 0.95 cm thick which are separated by 15.24 cm of air to afford some directional sensitivity. A 2.54 cm thick aluminum plate (equivalent to the range of a 12.2 MeV electron) is located in the gap between the paddles in order to reduce false coincidence due to delta rays produced by gamma rays or neutrons from the front paddle entering the rear paddle. This precludes false coincidences from all natural radioactive decay and many cosmic ray events. A minimum ionizing particle would deposit approximately 2 MeV in each paddle. The MERL paddles are located 121 cm above ground level. As used during the present measurements, both singles and coincidence events were counted on scalers during time periods gated in synchronization with the cycle of the accelerator using a microwave telemetry system (407 Mhz) which also transmitted primary beam intensity information. The scalers were gated such that the gate for one set of scalers was open during the beam spill (typically 1.5 seconds every 14 seconds at 350 GeV and 1.0 seconds every 14 sec at 400 GeV) to acquire "beam-on" data followed by a pause of approximately a second after which the gate on an alternate set of scalers was opened for a period equal to

the duration of the beam spill to acquire "beam-off" data in order to measure background radiation (principally due to cosmic rays).

In the present work a conversion of 28080 muons/cm^2·mrem was used. Equivalently, the conversion factor of 7.8 muons cm^{-2} sec^{-1} per mrem/hr was used for muons outside of thick shielding (all cases represented here). The value for minimum ionizing muons would be 8.7 muons cm^{-2} sec^{-1} per mrem/hr. During a typical year of 400 GeV operation approximately 2×10^{19} protons would be accelerated, extracted, and transported to the various primary targets. A typical target contributing significant muon fluxes would receive no more than 5×10^{18} protons during one year under present operating conditions. To be consistent with these magnitudes, the data presented below will be normalized in terms of mrem/10^{18} protons. In the data, error bars are the usual statistical ones indicating one standard deviation based upon Poisson counting statistics (including the subtraction of usually negligible background counts). Another possible source of error comes from the fact that beam intensities are monitored during data acquisition by scaling SEM (secondary emission monitor) pulse train outputs sent to the MERL by a telemetry system. Small (less than 10 per cent) errors result from truncation in these scaler readings. In all cases intensities were

known to better than 20 per cent.

The 15.24 cm separation of the paddles was chosen to afford a moderate directional sensitivity while not imposing an unacceptable positioning accuracy requirement upon the driver of the MERL vehicle. Of course it is not guaranteed that every muon incident on one of the paddles will be counted by both. For example, muons coming up out of the ground at some finite angle would be counted (using the coincidence requirement) at reduced efficiency. The singles events put in all cases an upper limit of a factor of two upon the error due to this effect at peaks of distributions. It is of interest that the ratio of singles to coincidences increases somewhat as one moves away from a peak of a plot of dose versus position. Directional sensitivity is the suspected cause of this problem, since off the peak the paddles were not adjusted to exactly face the more divergent spray of muons. At all locations the neutron flux was checked using the De Phanger Precision Long Counter mounted in the MERL and was found in all cases to be negligible compared with the muon flux as a source of dose equivalent.

During these measurements it has been useful to develop a set of standard reference locations from which the surveys were made. Table 1 is a list of these reference locations along with a brief description of them. In several cases

the data were taken along a line not perpendicular to the muon flight paths. In these cases the paddles were oriented within 5% of perpendicular by proper orientation of the MERL. The geometrical efficiency for a parallel beam of muons incident at 5 degrees on the apparatus would be 93 per cent. In all cases, the plots of dose/10^{18} primary protons versus position have been projected along a line perpendicular to the muon path (as determed by the peak dose location and the primary target location) and through the standard reference location. Figure 1 is a map of the relevant parts of the Fermilab site showing these reference locations.

Tables 2 and 3 list the number of protons delivered to the various primary targets during the two running periods under study, along with some commentary with respect to several specific beam lines. It will now be useful to discuss the results for the three experimental areas separately.

2. Meson Laboratory Muon Radiation Fields

In its present configuration the Meson Laboratory operates with two primary proton targets which feed six secondary beam lines. Of these the M4 line is underground and thus is not likely to contribute significant muon fluxes per proton compared with the others. The M5 is a test beam usually run at low intensity relative to the other 5. Of the other four, the M-Center primary target feeds M1, M2, and M3 while M6 runs off the M-West target. The muon radiation fields due to the operation of the Meson Laboratory are very complicated considering the presence of two primary targets and six secondary targets and their associated beam dumps. There are also many bend points which at a given moment are potential loss points and whose return yokes can bend the muon beams. In addition to these, another complication arises from the maze of tunnels and shielding. It is thus very difficult to determine exact sources of muons here without resorting to detailed, independent surveys of each secondary beam line and primary target implying some interference with the high energy physics program. Such surveys were not attempted here. The results reported here should be viewed as "snapshots" of the Meson area during typical running periods. The results are shown in Figs. 2, 3, and 4. In Figs. 2 and 3 the locations

of the secondary and primary beams are indicated (assuming straight ahead propagation from the last bend point). In Fig. 4, only the location of the primary beams has been indicated. These are intended to be suggestions of possible sources of muons. The normalization to the primary intensity is somewhat arbitrary and is based estimates based upon location. It seems sensible, for example to attribute the large peak at the west side in Fig. 2 to M-West rather than to M-Center. At locations further downstream, the data was simply normalized to the total number of Meson protons (during these measurement this total intensity amounts to roughly 1.25 times the M-Center intensity).

Significant differences between the two primary beam energies appear to exit in Figs. 2 and 3. However, these may be due to different operating conditions than to any energy dependence. The dose is quite low off-site and is quite conservatively less than 0.1 mrem/10^{18} protons (MC + MW) or about 0.2 mrem during the fiscal year 1981 running period (see Table 3). Fig. 10 shows the peak of the intensity distributions plotted as a function of distance from the primary target. The data has been somewhat arbitrarily normalized to the M-Center intensity. The $1/r^2$ dependence shown for comparison in Fig. 10 is normalized to the point at 1300 meters in order to exclude the effect of the upstream shielding hill. Fig. 12 shows a plot of full

width at half maximum (including both "peaks" in Figs. 2 and 3) plotted as a function of the distance from the primary target for the data. This gives one an idea of the divergence of the muon field. The dashed line in Fig. 12 is a linear least squares fit to the data and verifies expectations based upon the fact that multiple scattering in air for such high energy muons could be small, so that once the earth or concrete shield is escaped, very little deviation occurs. The elevation of the Meson area secondary beams is at 227.4 meters above sea level which is approximately the same elevation as the scintillation paddles in the MERL at the locations involved in the measurements. Also, the secondary beams are horizontal so that the muons measured upstream of the shielding hill are very likely on the same trajectories as the ones measured downstream of it so that the linear increase of FWHM with distance coupled with the rough $1/r^2$ dependence is reasonable.

3. Neutrino Laboratory Muon Radiation Field

The Neutrino Laboratory typically operates two primary proton targets, NØ and N7. A secondary beam of hadrons (usually π^-) or muons, N1, is derived from the slow spill component of the NØ beam and targeted just upstream of a

large magnetic spectrumeter (the Chicago Cyclotron magnet) in the Muon Laboratory. The NØ beam produces virtually no muons which escape the thick shielding required for the sensitive neutrino physics experiments it feeds. The N7 beam is used to produce a variety of hadron and electron beams for calibration purposes and was checked during both the 350 GeV (1980) and 400 GeV (1981) running periods and was found to not be a significant source of muons compared to the tail of the P-West muon field in which it lies. Thus the N1 secondary beam is the only significant source of muons from the Neutrino Laboratory. During the 350 GeV run N1 operated only with 225 GeV/c π^- and was inactive during the FY1981 400 GeV run. Because of the possibility of channeling the incident muon beam through the yoke of the cyclotron magnet, operation of N1 with a muon beam poses more difficult off-site muon problems. These have been investigated before.[1,2,3] In Ref. 3, it is stated that muon dose rates as large as 6 mrem/10^{18} protons were measured with muon beam operation at the site boundary.

For the 225 GeV/c π- beam run for Experiment 610 in 1980, measurements made at locations 2 and 4 are shown in Figs. 4 and 5. Figure 10 shows the peak dose rate plotted as a function of distance from the primary target, along with a $1/r^2$ dependence shown for comparison. Fig. 12 shows a plot of FWHM versus distance from the primary target. As

in the case of the Meson Laboratory secondary beams, the N1 incident beam is horizontally incident on the Muon Laboratory target and is at elevation 227 meters, roughly the same elevation as the paddles in the MERL. Thus the observation of a rough $1/r^2$ dependence of intensity with a linearly increasing FWHM is reasonable. In the present case one measures 0.3 mrem/10^{18} protons just inside of the Fermilab site boundary. During the 1980 350 GeV run, this would amount to 0.33 mrem at the worst off-site location.

4. Proton Laboratory Muon Radiation Fields

The Proton Laboratory operates three primary beam lines (P-East, P-Center, and P-West). The P-East and P-West usually involve relatively high intensity beams (typically 5 x 10^{12} protons per pulse) while P-Center usually runs at less than 10^{11} protons per pulse. The three beam lines are located approximately 3.6-4.6 meters underground so that their muon fields have to come out of the ground at an angle relative to the incident beam direction. The fact that the beam of muons is coming up out of the ground implies that, with a given detector at a fixed elevation, as one moves to increasing distances from the primary target one is measuring either muons produced at smaller production angles (implying production of higher momenta muons) which have

travelled through more shielding or skyshine muons. At this point it will be well to discuss in general terms the physics involved in muon transport to areas for downstream when the muons emerge from the ground as occurs in the Proton area as distinct from the "straight ahead" beams found in Neutrino and Meson.

The P-East and P-West primary beams are located at 223.4 meters elevation while the grade level downstream of the Proton area ranges in elevation between 225.6 and 227.0 meters. For example the data shown in Fig. 6 is 350 meters downstream of the P-East primary target which is 4.8 meters below the elevation of the detectors. Assuming the source of the muons to be a point near the location of the primary target where there is space allowing for pion decay, the detectors at this location are viewing muons deflected by some mechanism (production angle multiple scattering, etc.) to 12.9 milliradians. If the detectors remain at this same elevation (which they do with 2 meters), these muons need a deflection of 12.9 milliradians to reach the detectors at locations further downstream. From the range-energy curves of Ref. 4, the range of a 400 GeV muon in soil is about 700 meters so that the muons cannot be coming out of the earth shield much further downstream than this location. In Fig. 2 of Ref. 5 calculated momentum spectra of muons produced by 1000 GeV protons which have penetrated a thick

soil shield are given. From these curves it is seen that muon momenta averaging about 2 to 5 GeV/c will be seen by a detector sensitive only to flux (e.g., the paddles used here). This is conservative due to the 350-400 GeV primary energy considered in the present study. Applying Molieres' formulation of multiple scattering through air (see, for example the Particle Properties Data Booklet) one obtains a value for Θ_{rms} of 13.7, 19, and 23.7 milliradians at distances of 1000, 2000, and 3000 meters, respectively, downstream of the primary target. This implies that significant amounts of muons are scattered toward the earth's surface while the main "beam" escaping the earth shield is aimed upward at some small angle.

The γ ($\gamma = 1/\sqrt{1 - \beta^2}$) of a 2 GeV/c muon is 19 so that the time dilated mean life (assuming no de/dx in air), τ, is 4.2×10^{-5} sec. The mean length ($c\tau$) is then 12,500 meters so that the surviving fraction would be 0.92, 0.85, and 0.78 at 1000, 2000, and 3000 meters, respectively. The stopping power of air is about 0.0022 MeV/cm for minimizing particles. From Ref. 4 (roughly equating the mass stopping power of soil and of air), this is accurate within $\pm 30\%$ from 0.03 GeV to 200 GeV kinetic energies. So that in 3000 meters, 660 MeV is lost. Thus multiple scattering in the air sends muons back toward the surface (particularly the softer component) but also spreads them out and reduces the

flux. The energy loss in air causes them to slow down and reduces their survival fraction. Thus transport of Proton area muons to distant downstream areas is fairly complex, but could be carried out using Monte Carlo techniques beyond the scope of this paper. These considerations apply to both the P-East and P-West beam lines.

The muon dose rates are shown on Figs. 4, 6, 7, 8, and 9 and the dependences of intensity and FWHM upon distance from the primary target are shown in Figs. 11 and 13. The P-Center beam contributed insignificant muon rates compared with the other two beams. (at the above intensity) The P-East and P-West contributions will be discussed below.

During both the 350 GeV and 400 GeV running periods the P-East beam was used as a production target for the electron beam used in the Tagged Photon Laboratory (TPL). It is obvious that only slight differences are seen between 350 and 400 GeV at this location. It is also obvious that this muon beam is located on the center line of primary target since it is too far east to be centered on the electron beam dump. In Fig. 8 we see that at a somewhat more downstream location, a clean separation still exists between P-East and P-West and the intensity of P-East is reduced considerably while the peak has broadened, consistent with the presence of about 100 meters more soil shield if 6 GeV/c muons are

incident on it. In view of the spectra calculated by Stefanski and White[6] this magnitude of average energy would not be unreasonable.

In Figure 5 is shown a 350 GeV P-West distribution upstream at location 5 (which is approximately 100 meters upstream of location 8). The distribution here indicates that the muons are mostly originating in the primary target - momentum slit region as they are too far to the east to be coming from the secondary target. This location (location 7) was not accessible for 400 GeV 1981 measurements. Notice that while the location 8 P-West peak is broader, contrary to P-East case it is also more intense, indicating that the main muon beam is emerging from the ground between these two locations. In Fig. 8 some values of the abscissa have a data point for both P-West and P-East beams. This is the same number of events nomalized by both respective SEM readings used in attempt to separate the two sources by peak shape instead of using the directional sensitivity of the MERL paddles.

Fig. 9 shows Proton Laboratory data at location 7. Note that some data points were repeated with less than exact reproducibility. As one can see, the P-East intensity here is about 40 per cent higher at 400 GeV than at 350 GeV, consistent with increased secondary particle fields at the

higher energy. The FWHM remained about the same.

The P-West intensity at 400 GeV is only about half of the 350 GeV value. This is probably due to the installation of spoilers in the P-West beam line in the intervening period which successfully reduced backgrounds in the experimental hall. The FWHM seemed to remain about the same. The lack of exact reproducibility at this location from day to day is not surprising since here 10 meters represents only 10 milliradians at the primary target so that some sensitivity to exact operating conditions is likely.

Fig. 4 shown the 350 GeV data taken slightly outside of the site boundary. At this location the same data was plotted normalizing to either the P-East or the P-West SEM. From the close in data, it is suggested that P-East dominates the contribution to this unresolved peak.

Figs. 11 and 13 show the falloff of intensity and the rise of FWHM with distance from the primary target for these beams. As one can see, even with the complexities mentioned above, the suggestion of $1/r^2$ intensity dependence and linear increase of FWHM are still quite reasonable parameters of the muon fields at large distances. At the worst off-site location, P-East contributed at most 0.2

mrem/10^{18} protons or 0.64 mrem during the FY1981 running period while P-West (ignoring the above suspected domination of P-East would contribute about 0.2 mrem/10^{18} protons or 0.44 mrem during the FY(1981) running period. To sum these dose equivalents is reasonable however, because it was impossible to resolve the 2 beams at the site boundary.

In summary we see the the off-site dose equivalent from Fermilab produced muons during FY1980 and FY1981 is very low, less than 1 mrem for any single beam line. This dose equivalent is thus much lower than the Department of Energy limit of 170 mrem/yr and is still safely below the Laboratoy Director's limit of 10 mrem/yr. Only P-East and P-West of the present beam lines overlap to any significant extent. It appears that a $1/r^2$ dependence is a reasonable and conservative one to use in extrapolation to more distant locations. The P-East results point to more severe problems during Tevatron phase II operations because of the increased energy of the beam. For example, at location 7, P-East went from a peak of 0.8 mrem/10^{18} protons at 350 GeV to 1.1 mrem/10^{18} protons at 400 GeV. This is a 40 per cent change in dose for only a 14 per cent change in energy.

I would like to thank L. Coulson and S. Baker for their helpful comments. J. Phillips and R. Kingsley assisted in conducting the surveys with the MERL.

References

1. C. Moore and S. Velen, "Muon Beam Halo Studies", TM-497, June 11, 1974.

2. C. D. Moore, "Comparison of Halo Predictions with Experimental Measurements of Off-Site Muons Arising from 275 GeV/c Muon Line Operations", TM-680, August 10, 1976.

3. S. Velen and C. Moore, "Off-Site Radiation from Operation of Neutrino Area Muon Line at 225 GeV/c, TM-732, June 2, 1977.

4. G. Koizumi, "Muon dE/dx and Range Tables for Tevatron Energies: Results for Some Shielding Materials," TM-786, May 9, 1978.

5. A. Van Ginneken, "Penetration of Prompt and Decay Muon Components of Hadronic Cascades Through Thick Shields," TM-630, November 25, 1975.

6. R. J. Stefanski and H. B. White, "Neutrino Flux Distributions," May 10, 1976, FN 292.

Table 1

Description of Survey Reference Locations

1. East end of road north of Meson Detector Building. The survey was made along the road.

2. Center of intersection of Road A and Wilson Road. The survey for Meson area beams was conducted along Wilson Road and projected along a line perpendicular to the Meson area beams through this point. The survey for the N1 beam was made along Eola Road.

3. Center of intersection of Town and Roosevelt Roads. The survey was made along Roosevelt Road (Rt. 38).

4. Center of intersection of indicated road and Road A. The survey was made along the indicated road.

5. The survey was made halfway between the base of the P-West berm and the E258/326 Portakamp parallel to the base of the berm. The origin was referenced to the PW5 emergency exit hatch.

6. The survey was done along the road north of the Tagged Photon Laboratory with the origin referenced to the northeast corner of the TPL counting room.

7. The survey was referenced to the intersection of the Site 66 driveway and Wilson Road. The survey was made along Wilson Road and the results projected along a line perpendicular to the Proton area beams through this point.

8. The survey was referenced to the east end of the road behind the Proton Laboratory and was made along the road. The results were projected along a line perpendicular to the muon beam through this point.

Table 2

Protons Delivered to Fermilab Targets
March 21, 1980 through June 23, 1980

Primary Target	Total Protons Targeted at 350 GeV
P-East	6.25E17
P-Center [1]	4.11E15
P-West	4.90E17
NØ (Slow Spill) [2]	1.14E18
NØ (Fast Spill) [2]	6.66E17
N7 [3]	2.68E17
M-Center	1.06E18
M-West	1.08E18
Total Beam Accelerated	5.57E18

1. Muons not measured due to tuneup status.

2. NØ (slow spill) was used for the N1 measurements. NØ (fast spill) gives no contribution.

3. No muon flux was measured from this beam.

Table 3

Protons Delevered to Fermilab Targets
November 6, 1980 through June 1, 1981

Primary Target	Total Protons Targeted at 400 GeV
P-East	3.244×10^{18}
p-Center [1]	3.078×10^{16}
P-West	2.248×10^{18}
NØ (Slow Spill) [2]	8.372×10^{16}
NØ (Fast Spill) [2]	1.001×10^{19}
N7 [1]	9.655×10^{17}
M-Center	1.310×10^{18}
M-West	6.239×10^{17}
Total Beam Accelerated	1.764×10^{19}

1. No significant muon flux was measured for P-Center and N7-N3 operation.

2. No significant muon flux due to NØ targeting since N1 beam line was not used during this running period.

List of Figure Captions

1. Fermilab site with survey reference locations indicated.

2. Meson area muon fields near location 1. During the 1981 400 GeV muon survey M1E, M2, and M6W were operating.

3. Meson area muon fields near location 2.

4. Muon radiation fields near Fermilab site boundary.

5. Neutrino area muon fields near location 2. The data was taken on two different days (as shown) to check reproducibility.

6. P-East (Proton area) muon fields near location 6.

7. P-West (Proton area) muon fields near location 5.

8. Proton area (all three beams) muon fields near location 8.

9. P-East and P-West muon fields near location 7.

10. Meson (M-Center) and Neutrino (N1) maximum muon intensity plotted as a function of distance from the primary target. A $1/r^2$ dependence is shown for comparison.

11. Proton area (P-East and P-West) muon radiation fields peak intensity plotted as a function of distance from the primary target. A $1/r^2$ dependence is shown for comparison.

12. The full width at half maximum (FWHM) of the Meson M-Center and Neutrino N1 muon beams are plotted as a function of distance from the primary target. Linear least squares fits to the data are shown for comparison.

13. The full width at half maximum (FWHM) of the Proton (P-East and P-West) muon beams are plotted as a function of distance from the primary target. Linear least squares fits to the data are shown for comparison

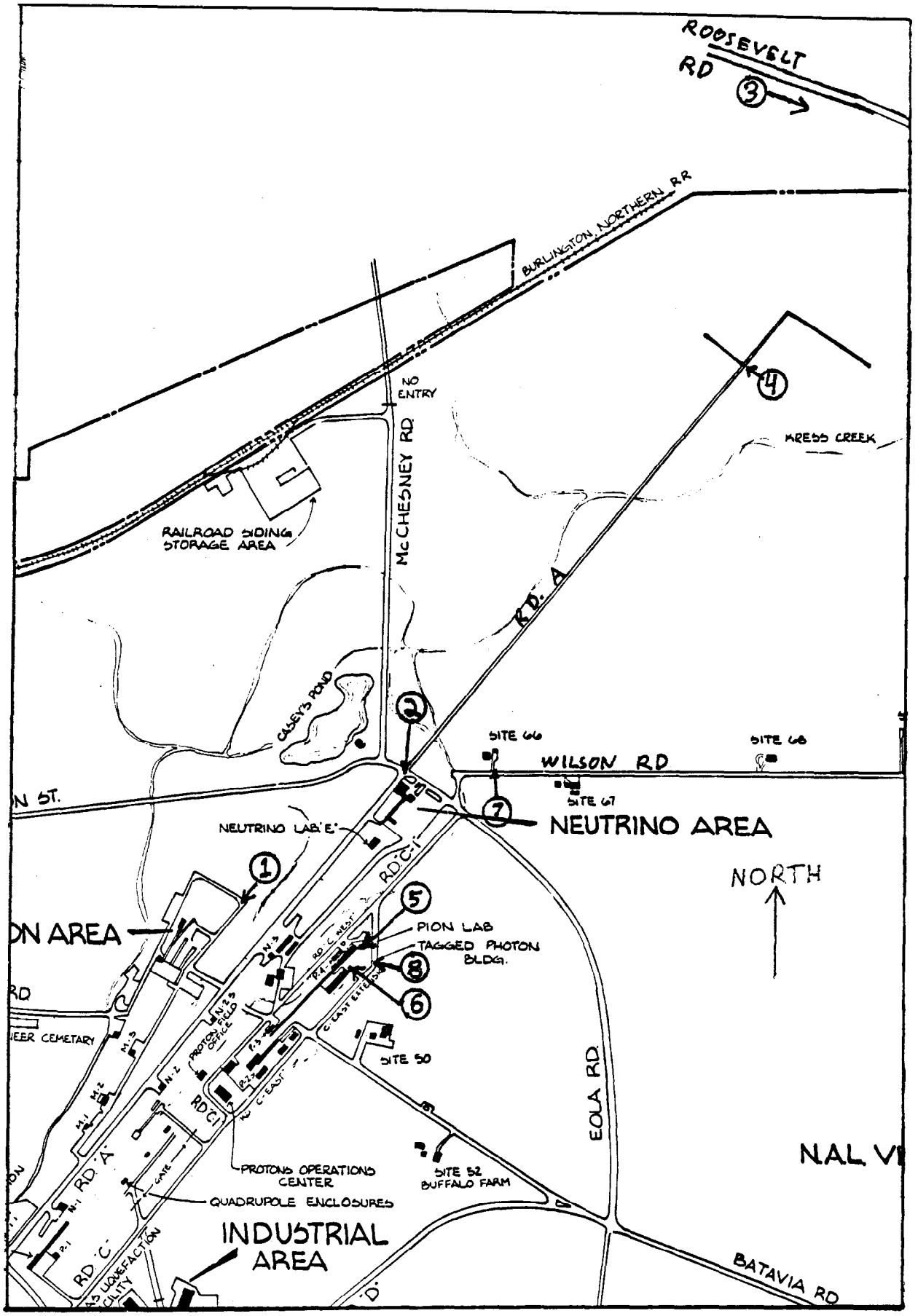

ROOSEVELT RD
BURLINGTON NORTHERN RR
NO ENTRY
McCHESNEY RD
KRESS CREEK
RAILROAD SIDING STORAGE AREA
RD. A
CASEY'S POND
SITE 66
SITE 68
WILSON RD
SITE 67
NEUTRINO AREA
NEUTRINO LAB 'E'
NORTH
PION LAB
TAGGED PHOTON BLDG.
RD 'C'
PROTON FIELD
PROTON OFFICE
SITE 50
EOLA RD
PROTONS OPERATIONS CENTER
SITE 52 BUFFALO FARM
QUADRUPOLE ENCLOSURES
INDUSTRIAL AREA
BATAVIA RD
RD 'A'
RD 'C'
GATE

FIGURE 1

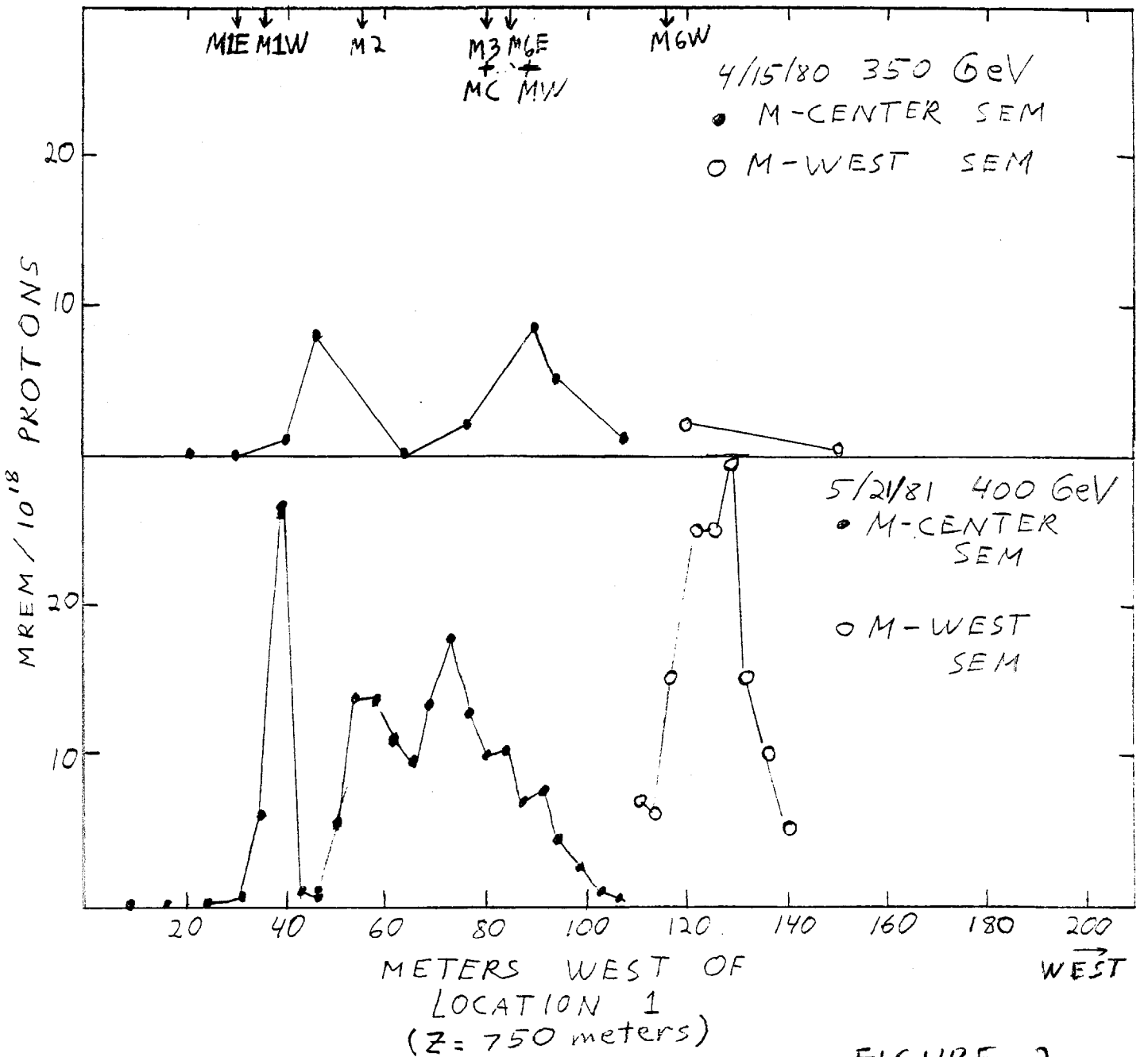

M1E M1W
M2
M3 M6E
MC MW
M6W
4/15/80 350 GeV
M-CENTER SEM
M-WEST SEM
5/21/81 400 GeV
M-CENTER SEM
M-WEST SEM
MREM / 10^18 PROTONS
20
10
20
10
20
40
60
80
100
120
140
160
180
200
METERS WEST OF LOCATION 1
(Z = 750 meters)
WEST

FIGURE 2

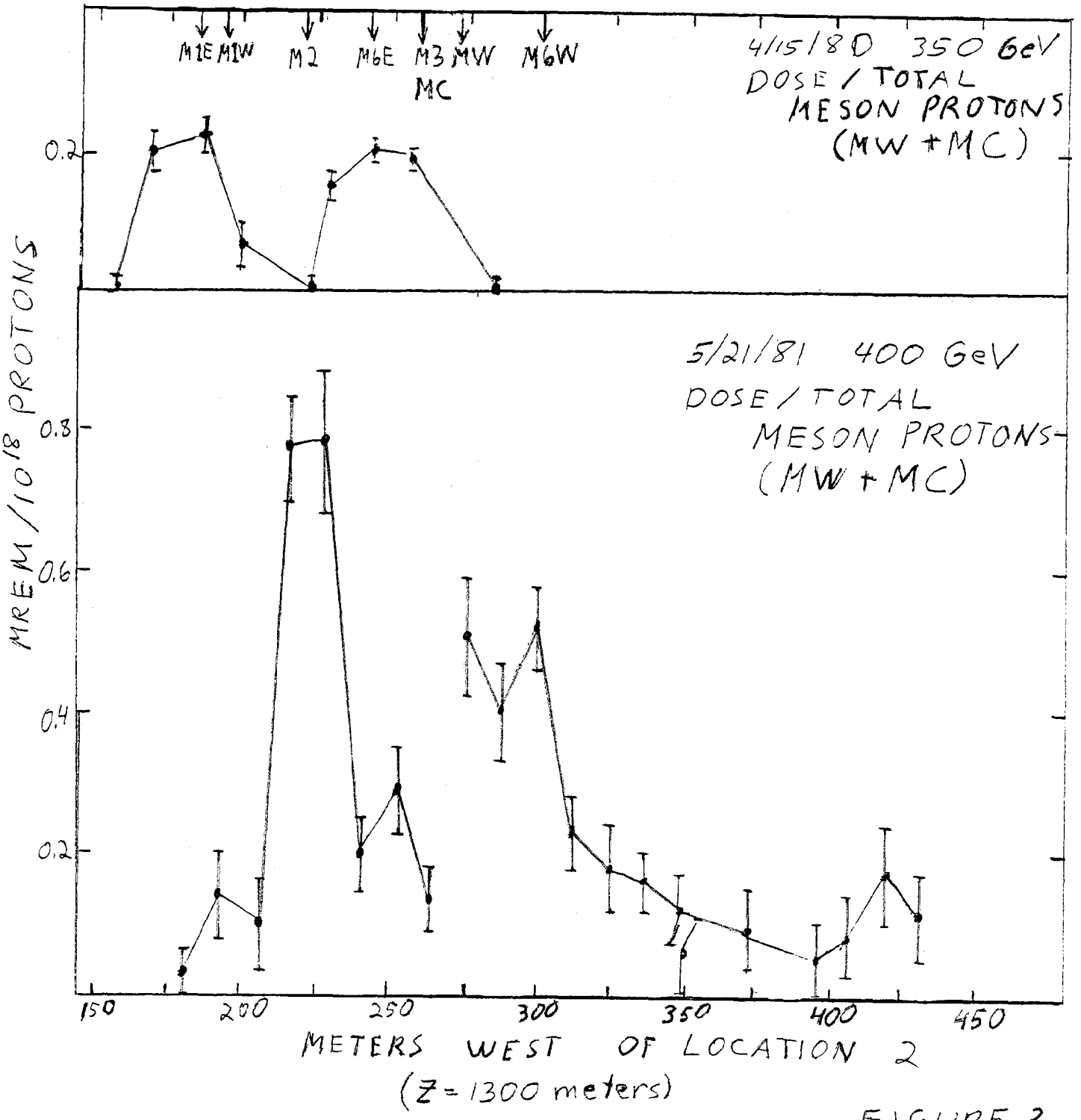
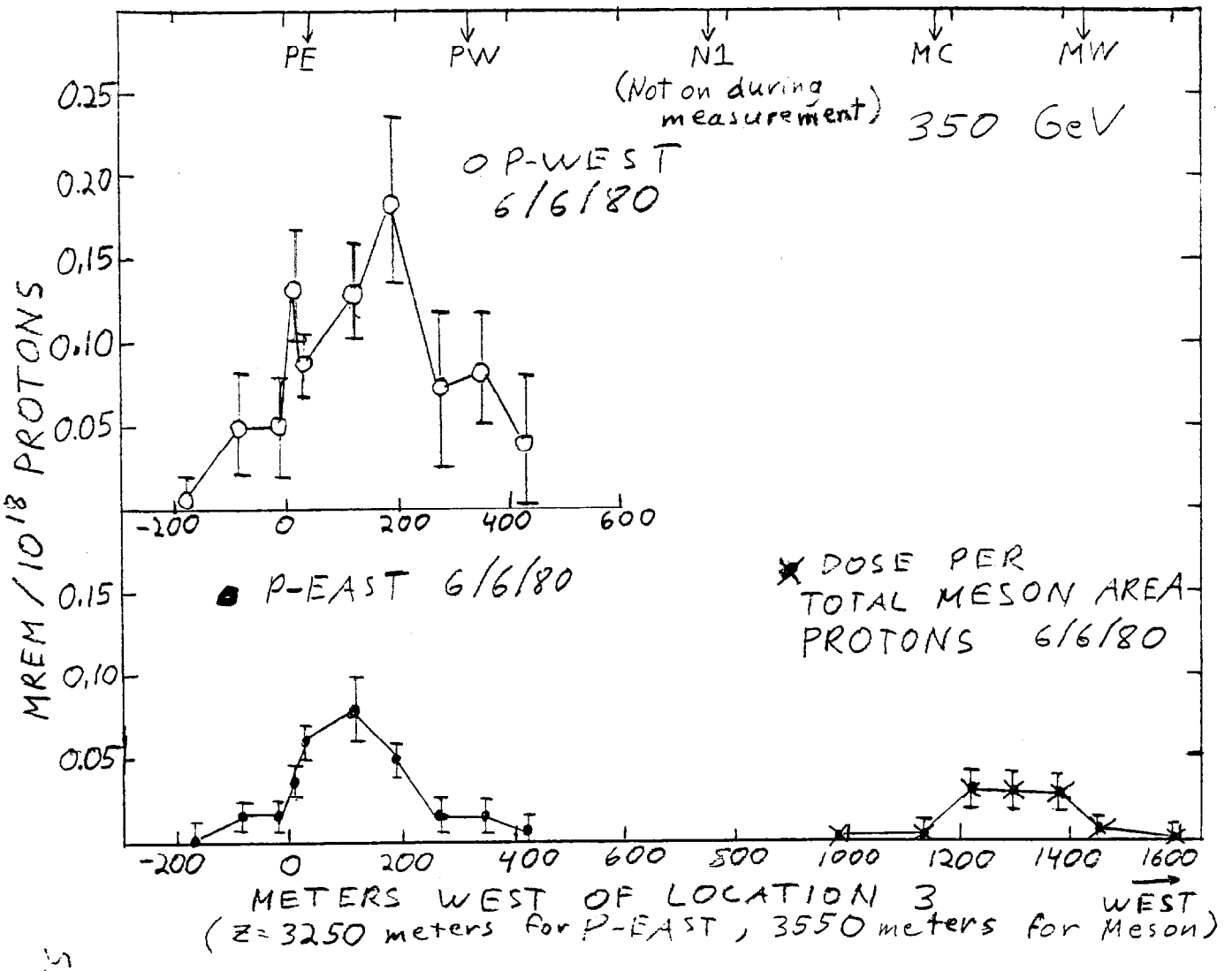

M1E M1W M2 M6E M3 MW M6W
MC
4/15/80 350 GeV
DOSE / TOTAL
MESON PROTONS
(MW + MC)
0.2
5/21/81 400 GeV
DOSE / TOTAL
MESON PROTONS
(MW + MC)
0.8
0.6
0.4
0.2
MREM / 10^18 PROTONS
150
200
250
300
350
400
450
METERS WEST OF LOCATION 2
(Z = 1300 meters)

FIGURE 3


PE
PW
N1
(Not on during measurement)
MC
MW
350 GeV
O P-WEST 6/6/80
P-EAST 6/6/80
DOSE PER TOTAL MESON AREA PROTONS 6/6/80
MREM / 10^18 PROTONS
0.25
0.20
0.15
0.10
0.05
-200
0
200
400
600
500
1000
1200
1400
1600
METERS WEST OF LOCATION 3
WEST
(Z = 3250 meters for P-EAST, 3550 meters for Meson)

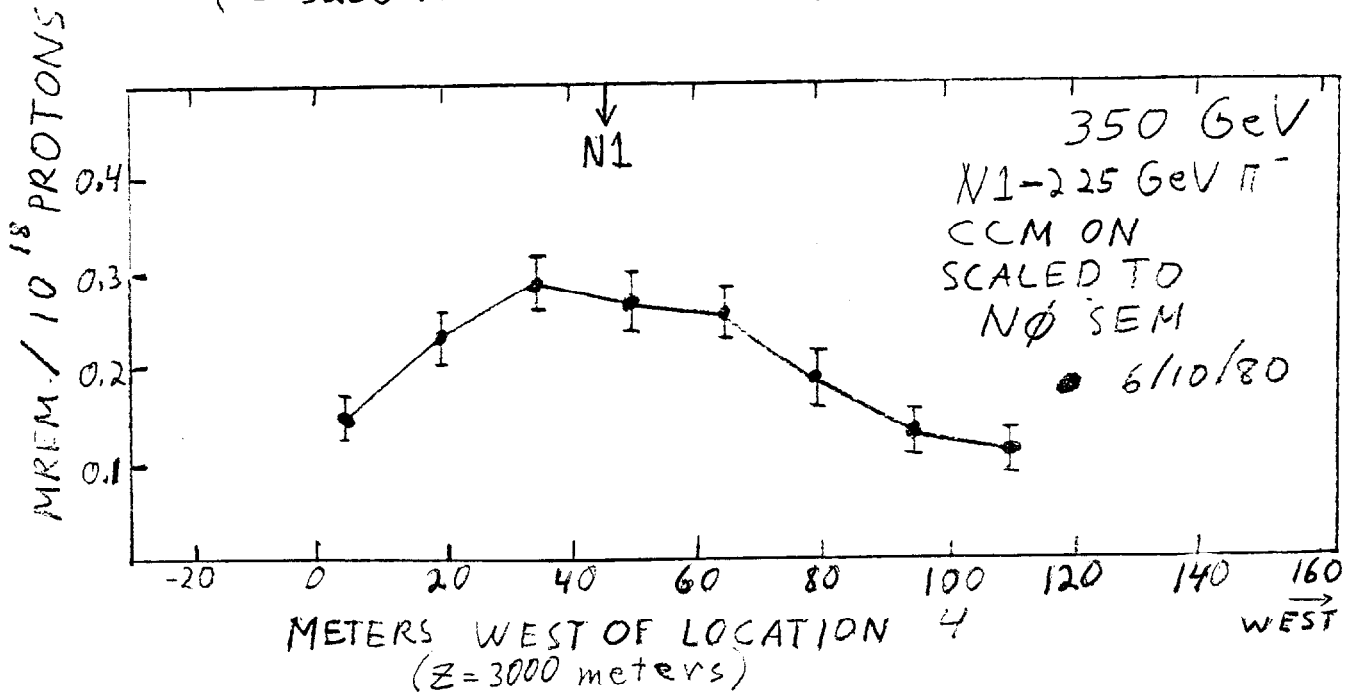

N1
350 GeV
N1-225 GeV π⁻
CCM ON
SCALED TO
NØ SEM
6/10/80
MREM / 10^18 PROTONS
0.4
0.3
0.2
0.1
-20
0
20
40
60
80
100
120
140
160
METERS WEST OF LOCATION 4
WEST
(Z = 3000 meters)

FIGURE 4

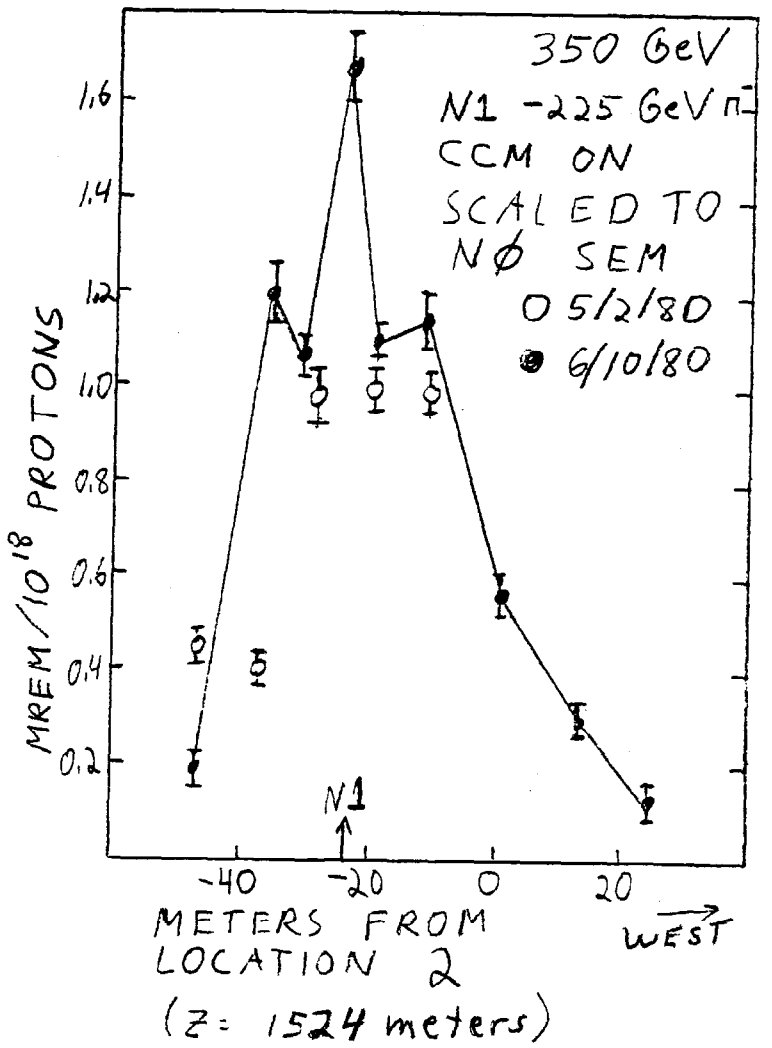

350 GeV
N1 -225 GeV π⁻
CCM ON
SCALED TO
NØ SEM
O 5/2/80
● 6/10/80
MREM/10^18 PROTONS
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
N1
-40
-20
0
20
METERS FROM
LOCATION 2
(Z= 1524 meters)
WEST

FIGURE 5

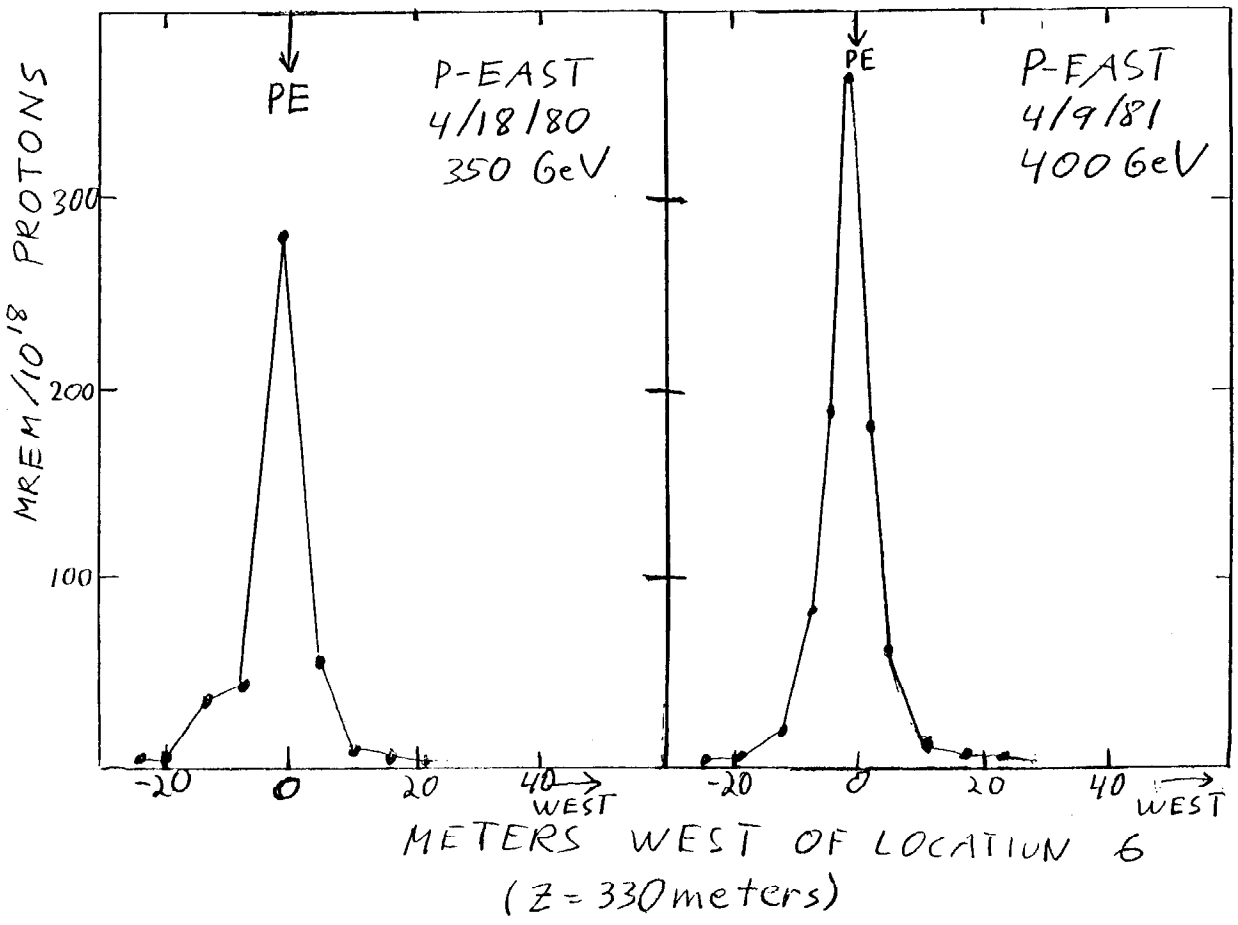

PE
P-EAST
4/18/80
350 GeV
PE
P-EAST
4/9/81
400 GeV
MREM/10^18 PROTONS
300
200
100
-20
0
20
40
WEST
-20
0
20
40
WEST
METERS WEST OF LOCATION 6
(Z = 330 meters)

FIGURE 6

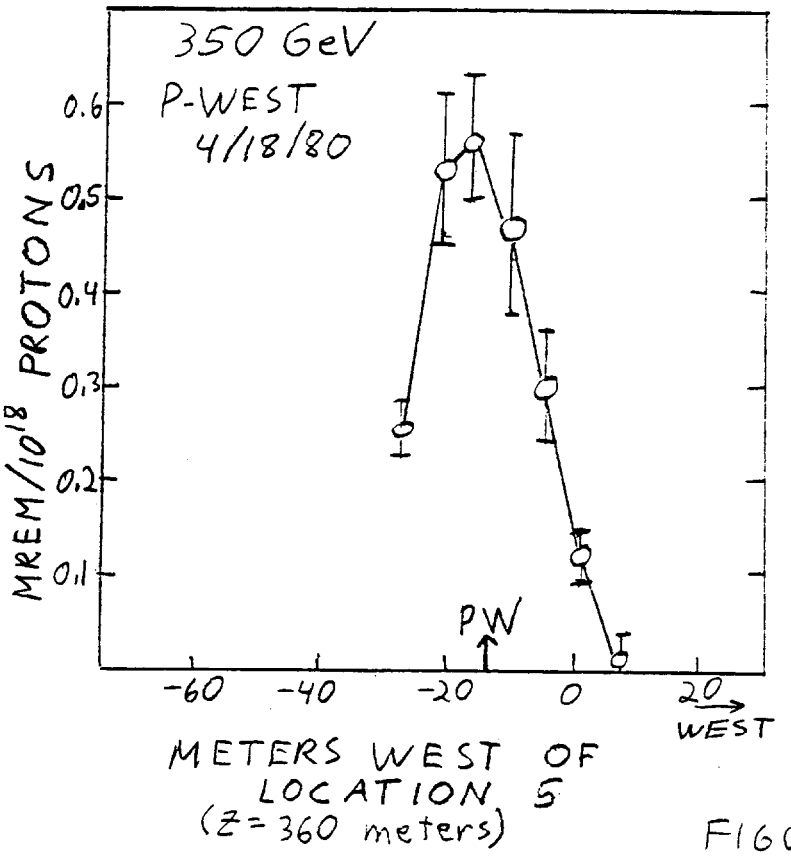


FIGURE 7

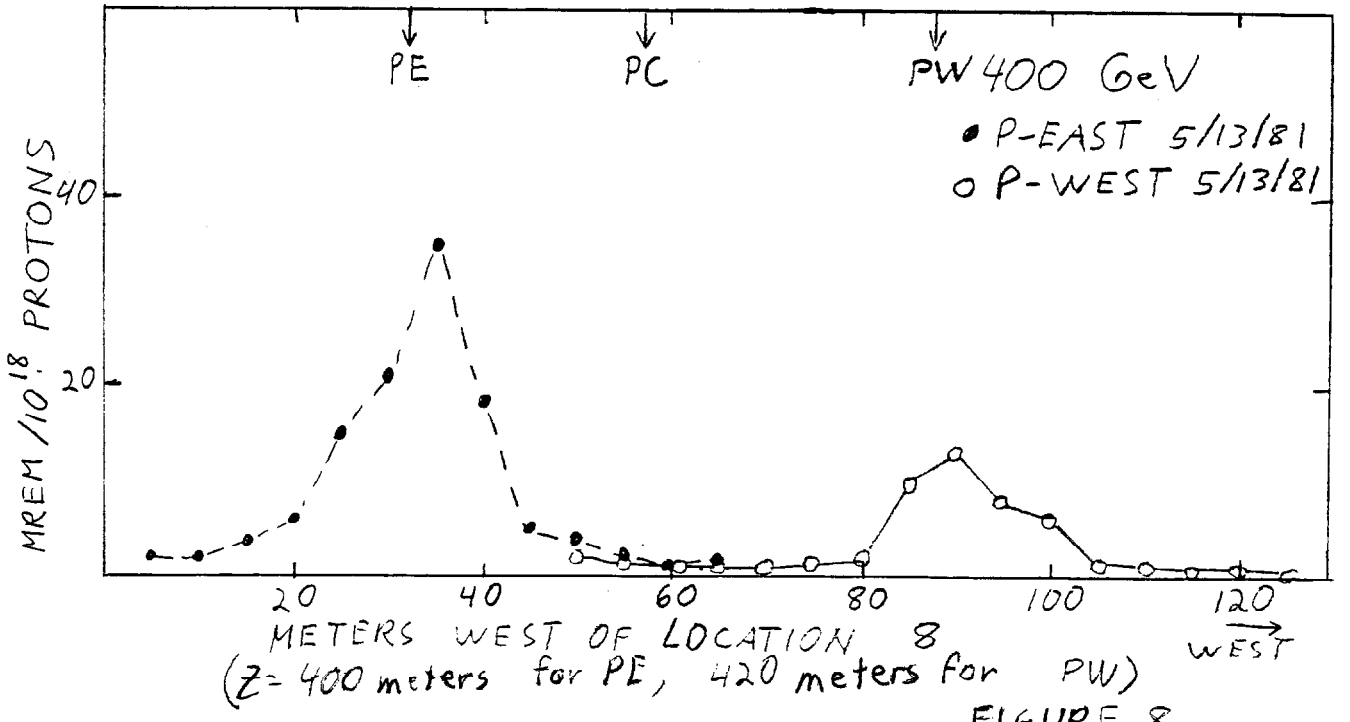


FIGURE 8

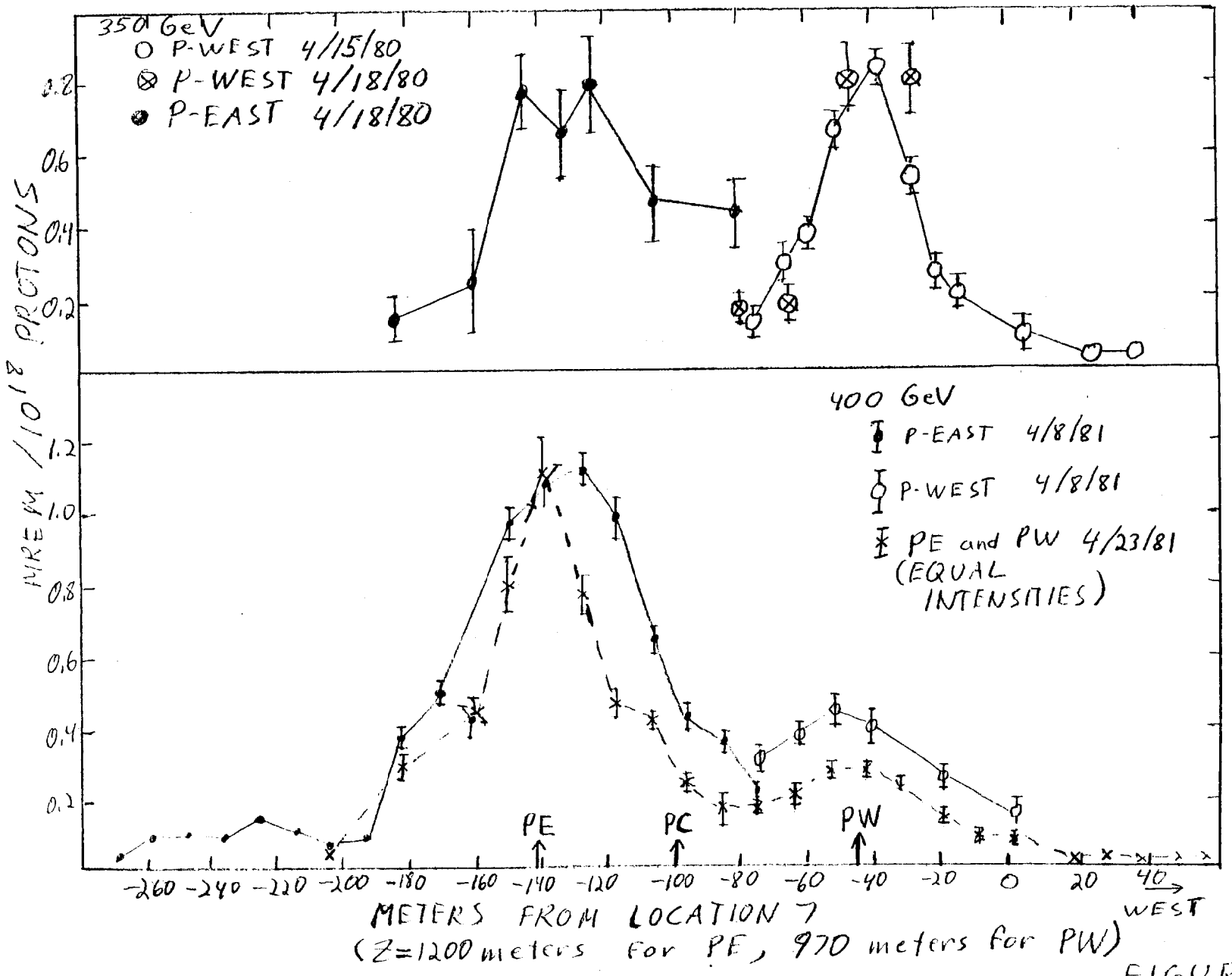

350 GeV
O P-WEST 4/15/80
⊗ P-WEST 4/18/80
● P-EAST 4/18/80
0.8
0.6
0.4
0.2
MREM / 10^12 PROTONS
400 GeV
P-EAST 4/8/81
P-WEST 4/8/81
PE and PW 4/23/81
(EQUAL INTENSITIES)
1.2
1.0
0.8
0.6
0.4
0.2
PE
PC
PW
-260 -240 -220 -200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40
WEST
METERS FROM LOCATION 7
(Z=1200 meters for PE, 970 meters for PW)

FIGURE 9

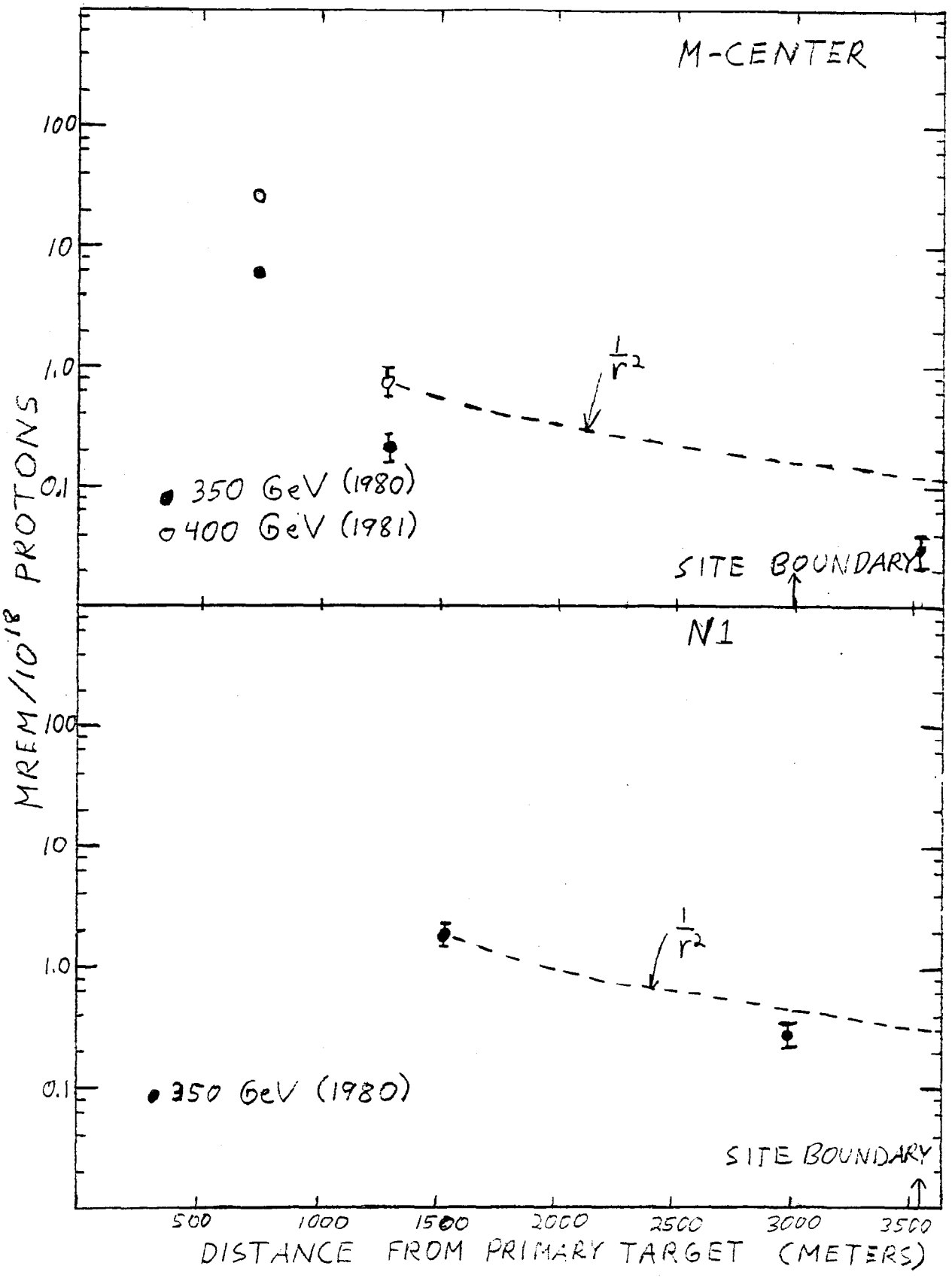

M-CENTER
100
10
1.0
0.1
$\frac{1}{r^2}$
350 GeV (1980)
400 GeV (1981)
SITE BOUNDARY
N1
100
10
1.0
0.1
$\frac{1}{r^2}$
350 GeV (1980)
SITE BOUNDARY
MREM/10^{18} PROTONS
500
1000
1500
2000
2500
3000
3500
DISTANCE FROM PRIMARY TARGET (METERS)

FIGURE 10

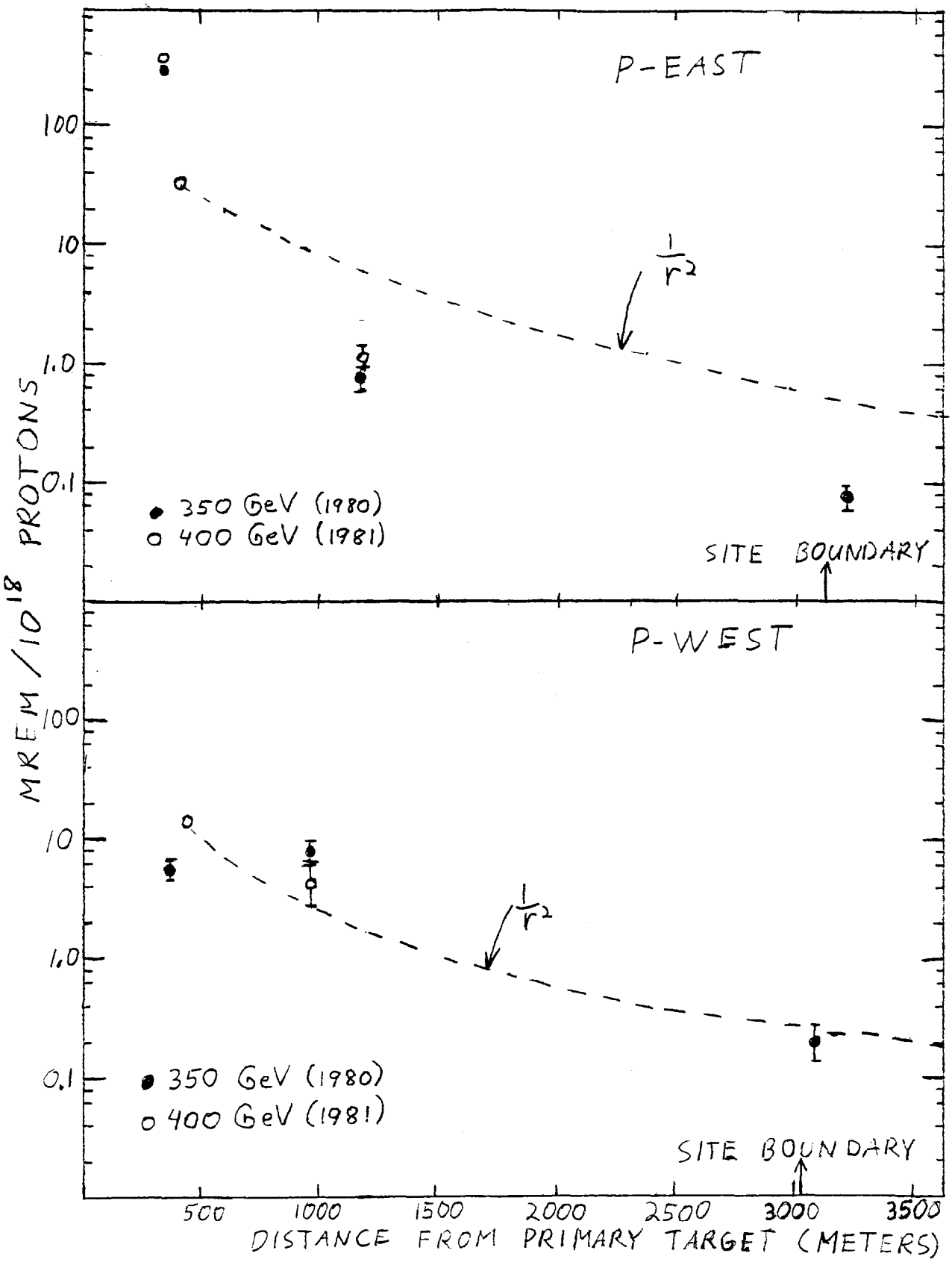

P-EAST
P-WEST
100
10
1.0
0.1
MREM / 10^{18} PROTONS
$\frac{1}{r^2}$
350 GeV (1980)
400 GeV (1981)
SITE BOUNDARY
500
1000
1500
2000
2500
3000
3500
DISTANCE FROM PRIMARY TARGET (METERS)

FIGURE 11.

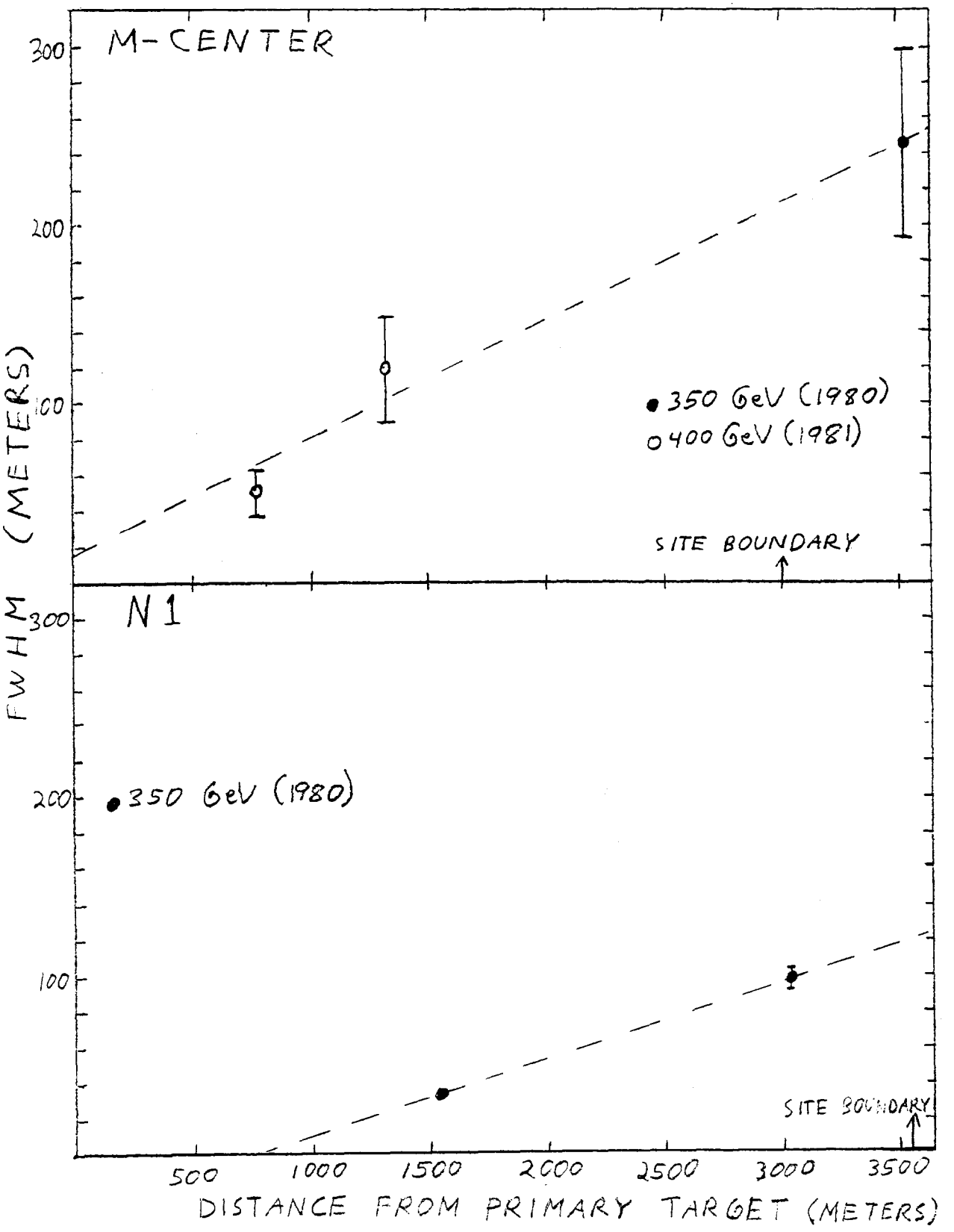

M-CENTER
300
200
100
FWHM (METERS)
• 350 GeV (1980)
○ 400 GeV (1981)
SITE BOUNDARY
N1
300
200
100
• 350 GeV (1980)
SITE BOUNDARY
500
1000
1500
2000
2500
3000
3500
DISTANCE FROM PRIMARY TARGET (METERS)

FIGURE 12

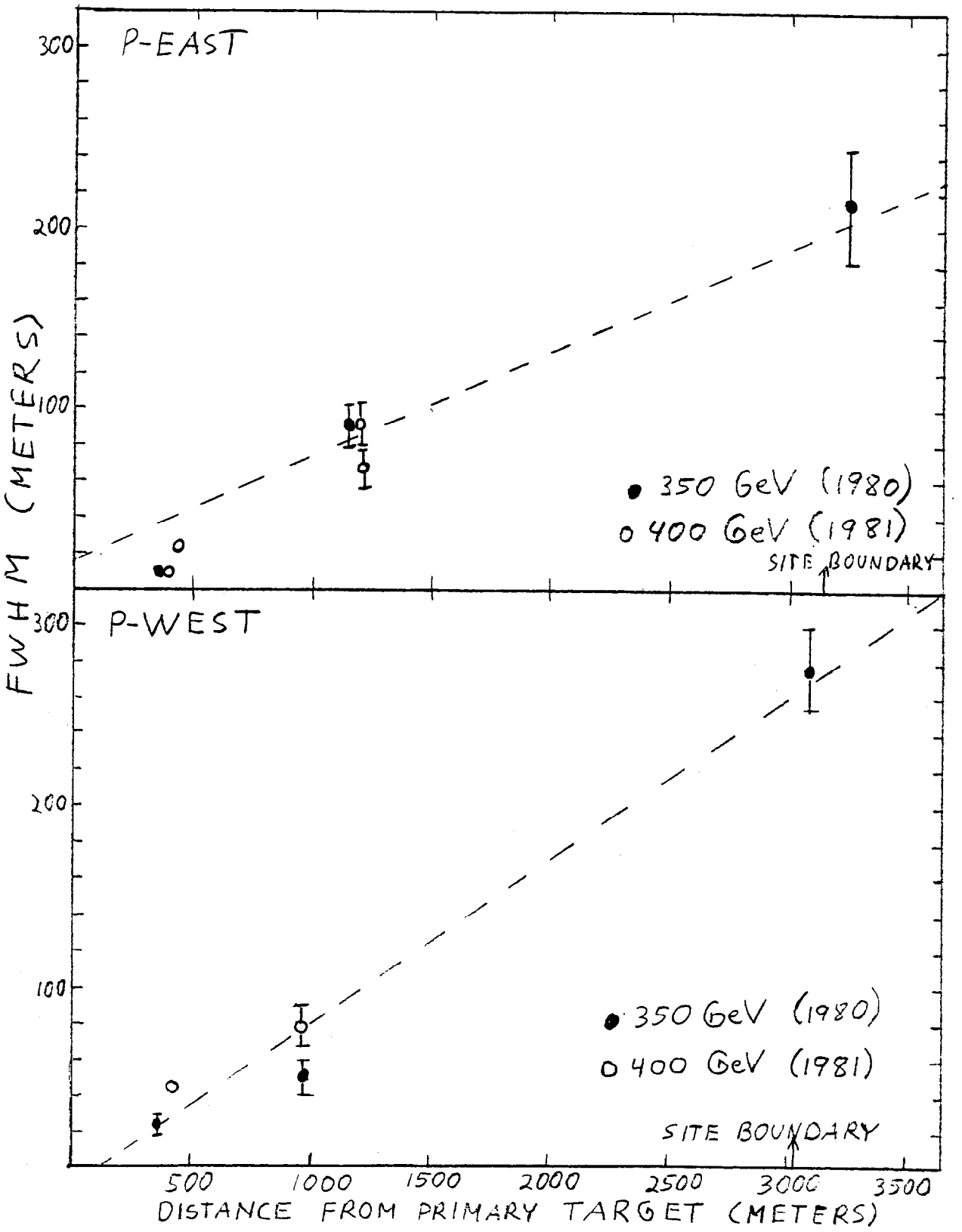

P-EAST
P-WEST
FWHM (METERS)
300
200
100
300
200
100
350 GeV (1980)
400 GeV (1981)
SITE BOUNDARY
350 GeV (1980)
400 GeV (1981)
SITE BOUNDARY
500
1000
1500
2000
2500
3000
3500
DISTANCE FROM PRIMARY TARGET (METERS)

FIGURE 13