SLAC-PUB-906
UCRL-20634

ZENITH-ANGLE DISTRIBUTION OF ATMOSPHERIC MUONS ABOVE 1 TeV*

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March 1971

ABSTRACT

The flux of atmospheric muons as a function of momentum and zenith angle is measured for $p > 0.3$ TeV and $60° < \theta < 87°$. Special attention is given the angular distribution above 1 TeV.

(Submitted to Physics Letters B)

In 1967, Bergeson et al. [1] published data from an underground cosmic ray experiment, suggesting that a new process is occurring in nucleon-nucleon interactions at energies of several TeV. They observed the angular distribution of muons penetrating to great depths underground, and instead of finding the enhancement at large zenith angles that is expected if muons are produced by the decay of pions and kaons, they saw an isotropic distribution. The simplest interpretation of these results was that a substantial fraction of muons above 1 TeV are produced directly or via a very short-lived parent, since it is the intermediate long-lived parents (pions and kaons) in the conventional model that give the enhancement at large zenith angles, owing to the competition between interaction and decay in the upper atmosphere. Subsequent results from the same group [2] indicated that the fraction of directly produced muons is much smaller than the original paper had suggested.

An underground experiment from the Kolar gold fields [3] has disagreed with the Utah results. The contribution of magnetic spectrometers to this question has been mainly at energies below those corresponding to the Utah experiment's depths. No anomalies have been seen at 0.3 TeV [4] and up to 1 TeV [5]. Both criticism and support of the Utah results have been based on indirect relationships to other cosmic-ray experiments; for a general survey of experiments up to November 1970, see refs. [6] and [7].

It is clear that such a new process would have great impact on particle physics. A discussion of some of the implications of anomalous muon production is given by Bjorken et al. [8].

In an effort to avoid the uncertainties in an underground experiment caused by the passage of muons through large amounts of rock, we have performed a magnetic spectrometer experiment at sea level, with optical spark chambers and an air-gap magnet. Our experiment was set up in the experimental yard at the Stanford Linear Accelerator Center. Since the expected enhancement from the conventional model increases with zenith angle, our experiment covers large zenith angles (θ) from 60° to 87°, with a total geometry factor of 570 cm^2-sr. We report here on the high energy events from about 70% of our data, representing a running time of 2.05×10^6 s. The number of particles above 0.3 TeV is 2500.

Experimental Details. A schematic of the apparatus is shown in fig. 1. The 70 mm camera viewed the apparatus from 20 meters away with no intervening mirrors so that the bent trajectory of the particle was imaged directly on the film, with a demagnification of 100. Each chamber had several gaps. A 90° stereo view was provided by mirrors underneath each chamber (except chamber 5). A 25-radiation-length lead wall was erected in front of the entire apparatus to attenuate any showers which might accompany the very high energy muons. The magnet had a field integral of nearly 30 kG-m, which will bend a 1 TeV particle by 1 mrad. Sixteen plastic fiducials, which were illuminated for each picture, were distributed over the field of view.

The apparatus was triggered by selected, straight-line, triple coincidences between scintillation-counter hodoscopes A, B, and C. The planes A and C each consisted of nine 54-cm-wide, 117-cm-long, 2-cm-thick plastic scintillators with lucite light pipes and 5 inch phototubes, while the B plane was twelve 18-cm-wide, 92-cm-long, 2-cm-thick plastic scintillators with 2 inch phototubes. These counters were shown, in tests at the Bevatron in Berkeley, to be more than 99 % efficient. The B plane was arranged so that three adjacent B counters always lay precisely on a straight line between an A and a C counter. The effective low-energy cutoff of the trigger was about 5 GeV. The trigger rate was 0.5/s, about 20% being extensive air showers which often triggered many counters in each plane. Events of this type were accepted in order to avoid any possible bias against multitrack events. (The pictures with muons above 1 TeV contain one and only one track more than 95 % of the time. Thus other large-zenith-angle magnetic-spectrometer experiments with apertures comparable to or smaller than $4m^2$ should not have a significant bias from the rejection of multitrack events.)

During the run, a PDP-8 computer recorded which counters fired and the live time since the last event. This information, which is stored on magnetic tape, allows an accurate calculation of the running time for any part of the experiment, as well as a careful study of any drifts in counter efficiency.

The entire run resulted in 1.6 million pictures, of which 1.0 million have been used here. A program is under way to analyze the data for all momenta above 20 GeV. However, for the present results, the film was scanned in order to select only high energy events. The scanning process consisted of comparing the scan-table image of a track with a straight ruler, and rejecting events which deviated too far from a straight line. In this way the scanners were able to pick all events that have a bend angle less than 6 mrad ($p \gtrsim 0.16$ TeV) with 95% efficiency. The selected high energy events were measured on conventional film plane digitizers. All reconstructed events were required to satisfy a fiducial volume test, and only events which fired chamber 3, chamber 4, at least one of chambers 1 and 2, and at least one of chambers 5 and 6 were accepted. Each track was fitted to a line bent at the point of symmetry with respect to the magnet center. The constraints thus imposed allow an internal estimate of the accuracy of position for each chamber; it varied from 650 μ at $\theta = 87°$ to 1000 μ at 60°. The resulting momentum accuracy is such that a 100% (rms) error is achieved at 2 TeV for 87° and 1 TeV for 60°.

Assurance that the random error in momentum measurement is well understood and that systematic errors are small is crucial to the correct determination of the momentum spectrum and angular distribution of the high energy muons in our experiment. The systematic shifts due to optical distortion have been corrected by comparing the positions of the fiducials as measured on the film plane digitizers with the positions as surveyed *in situ* to an accuracy of 250 μ. Two independent checks were made: first, a laser beam traveling alongside the spark chambers in the general direction of the real tracks was photographed and the straightness of the line on the film was verified; second, the charge ratio of events with $p > 0.3$ TeV for the two polarities of the magnet were compared. The second test proved that the systematics remaining after corrections are less than 0.3 mrad. These tests were made as a function of zenith angle.

Finally a completely independent test of both systematic and random errors was made by photographing two sets of tracks with the magnet off. First, a beam from the Stanford Linear Accelerator of 12 GeV muons was sent through at $\theta = 90°$. The results of measuring these pictures are shown in fig. 2a. Second, a large-aperture Cerenkov counter was used to select atmospheric muons at $\theta = 60°$ with momentum greater than 4 GeV. The results are shown in fig. 2b. The curves in fig. 2 are the result of calculations based on our completely independent knowledge of the measurement errors, and they agree well with the histograms. Multiple scattering, which would have widened the curves only slightly, has not been included in the calculation.

In order to present the data in the most useful way, the momenta of all particles have been corrected to the "top of the atmosphere"; the 100 g/cm^2 level was chosen. In this correction, account was also taken of a hill which particles of $\theta > 81°$ had to penetrate. The hill varied from 60 hg/cm^2 at 81° to 280 hg/cm^2 at 87° (hg = hectogram).

Results. After analysis, 2492 particles with momenta greater than 0.3 TeV and $60° < \theta < 87°$ are available. Rather than deal with momentum, whose error is very skew when it approaches 100%, it is desirable to use the variable $k = 1/p$, whose error, even when large, is symmetric. Any spectrum in p will transform into a spectrum in k as $dN/dk = p^2\ dN/dp$. (For example, a p^{-3} differential momentum spectrum transform to $dN/dk \propto k$.) The sign of k is equal to the sign of charge of the particle.

Figure 3 shows the k spectra for three regions of zenith angle covering the range of our experiment. The horizontal bars indicate the average error in k for that region of θ. Because of these measurement errors, the observed spectra near $k = 0$ are increased substantially over the true spectra. Any theory must take these errors into account.

In a preliminary theoretical analysis of our data, we have fitted our distribution in p and θ to the following phenomenological form:

$$\frac{dN}{dt\,dp\,d\Omega} = DSp^{-\gamma}\left\{\frac{B_\pi}{p\cos\theta^* + B_\pi} + \frac{R\,B_k}{p\cos\theta^* + B_k} + x\right\}/Q,$$

$$Q = \frac{B_\pi}{1 + B_\pi} + \frac{R\,B_k}{1 + B_k},$$

where $B_\pi = 0.09$ TeV, $B_K = 0.45$ TeV, and $R = 0.3$. For positively charged particles, $S = C$; for negative particles, $S = 1$. Thus C is the muon charge ratio. θ^* is the zenith angle at the top of the atmosphere. The unknown parameters are D, C, γ, and x. If $x=0$, this form represents a rather crude approximation to the conventional model [9] where γ is the power of the differential spectrum of produced pions and kaons (approximately equal to the spectrum of primary cosmic ray protons), and R is the charged K/π ratio. A very similar functional form was used by Keuffel et al. [2] in the analysis of their data. The parameter x represents an isotropic component of muons produced in a fixed ratio to pions and kaons. In our analysis the simplifying assumption has been made that x does not depend on p. A maximum-likelihood technique has been used for the fitting, which also incorporates the effect of measurement errors event by event.**

Since the absolute normalization of our experiment is known to within 20%, it is possible to include information from other experiments at $\theta = 0°$, which can be done in many ways. It was decided to use the known integral above 1 TeV of muons at 0° as a constraint. The value is $5.1 \times 10^{-8}/\mathrm{cm}^2$-sr - s [10]. The claimed accuracy of this integral is 20%; it has been used in our fits with an error of 30%, to account for our own absolute normalization uncertainty.

The results of the fits are shown in table 1, where we include fits with and without the absolute normalization constraint, and with and without allowance for non-zero x.

Figure 4 shows the angular distribution of muons above 1 TeV from our experiment, where corrections have been made for momentum resolution. The solid curve represents our best fit to the conventional model with the normalization constraint. From table 1 and fig. 4, no evidence is seen for any anomalous process in the production of muons integrated above 1 TeV. The charge ratio of 1.24 ± 0.05, for events above 0.3 TeV, shows no change from lower energy determinations. Our fits imply a logarithmic derivative of the muon momentum spectrum at 1 TeV in the vertical of -3.40 ± 0.05, which is in reasonable agreement with other results [11].

The angular distribution that we obtain can be compared with the angular distribution obtained by Keuffel et al. for their smallest depths. Since a depth underground is not directly translatable to a momentum, an absolute intensity comparison is very difficult. However, the Utah group has established a world-survey vertical depth-intensity curve, and they have plotted their enhancements above the vertical flux as a function of $\sec \theta^*$ at each of their depths. In order to compare angular distributions we have chosen $6.8 \times 10^{-8}/cm^2$-sr-s as our reference vertical flux (this is the value obtained in the best fit to the conventional model with absolute normalization). In fig. 4 we have plotted the Utah 2400 hg/cm^2 enhancements over this reference value. Thus the Utah points in fig. 4, although not plotted with the correct absolute normalization, can be directly compared with the theoretical curves. It is known that the smallest depth values (2400 hg/cm^2 and 3200 hg/cm^2) or Keuffel et al. [2] roughly correspond to a 1 TeV threshold for muons to penetrate the rock. We have determined that their angular distributions at 2400 hg/cm^2 and 3200 hg/cm^2 are rather well represented by $x = 0.02$ and $x = 0.05$ respectively.***

Our conclusions are:

1) We see a substantial enhancement at large zenith angles for muons above 1 TeV, in strong disagreement with the original paper of the Utah group [1].

2) Without the inclusion of any absolute normalization constraint our data are not sensitive enough to test the size of the effect in the latest Utah results [2].

3) If we include a constraint based on the vertical flux of muons above 1 TeV, with an error of 30%, we then disagree with the latest Utah results by between 2 and 3 standard deviations, assuming the specific model considered here. We wish to strongly point out, however, that at the level of 5% x process the approximations of the crude phenomenological model we are using in this preliminary analysis are very suspect, especially at large sec θ^*, and it would be very desirable to utilize a more sophisticated calculation of the

theory [6]. It is important to note that the Utah data at 2400 hg/cm^2 (~ 1 TeV threshold, corresponding to our energies) cover a completely different angular range than does our experiment. The Utah data at larger depths, for which we have no comparable data, reach to larger $\sec\theta^*$ than their 2400 hg/cm^2 data.

These conclusions are not sensitive to a systematic error in our measurement of k of as much as 0.5 TeV^{-1}, nor are they sensitive to misestimation of our resolution by as much as 20%. Assumption of a threshold a 1 TeV for short-lived parents in the x process also does not alter our conclusions.

We emphasize that any comparison between previous results and our own is model dependent. We regard our experiment as providing a significant reduction in the number of possible theories for high energy muon production.

Acknowledgments

We thank the staffs of the Stanford Linear Accelerator Center and the Lawrence Radiation Laboratory for their cooperation in mounting and analyzing this experiment, and especially SLAC Group E under Professor M. Perl for providing a large part of the apparatus. We are grateful to the University of Utah Cosmic Ray Group under Professor J. Keuffel for providing many of their results prior to publication, and for many discussions.

Footnotes and References

*Work done under the auspices of the U. S. Atomic Energy Commission.

**The program OPTIME was used; see P. H. Eberhard and W. O. Koellner, Lawrence Radiation Laboratory Report UCRL-20159, Oct. 1970.

***This calculation was done with a list of probabilities for a muon of a given energy to penetrate a given amount of rock provided to us by J. Keuffel and J. Morrison of the University of Utah. (University of Utah Cosmic Ray Note No. 108, Jan. 1971.)

1. H. E. Bergeson, J. W. Keuffel, M. O. Larson, E. R. Martin, and G. W. Mason, Phys. Rev. Letters 19 (1967) 1487.
2. J. W. Keuffel, J. L. Osborne, G. L. Bolingbroke, G. W. Mason, M. O. Larson, G. H. Lowe, J. H. Parker, R. O. Stenerson, and H. E. Bergeson, 11th Int. Conf. Cosmic Rays, Budapest, 1969, MU 31. See also H. E. Bergeson, J. W. Keuffel, M. O. Larson, G. W. Mason, and J. L. Osborne, Phys. Rev. Letters 21 (1968) 1089.
3. M. R. Krishnaswamy, M. G. K. Menon, V. S. Narasimham, S. Kawakami, S. Kino, and S. Miyake, Phys. Letters, 27B (1968) 535.
4. R. J. Stefanski, R. K. Adair, and H. Kasha, Phys. Rev. Letters 20 (1968) 950.
5. J. G. Asbury, W. A. Cooper, L. Voyvodic, R. J. Walker, and T. P. Wangler, Nuovo Cimento 66B (1970) 196. See also W. F.

Nash and A. W. Wolfendale, Phys. Rev. Letters 20 (1968) 698.

6. Kaichi Maeda, "Zenithal Distributions of Atmospheric Muons at Mt. Chacaltaya," Preprint X-641-69-491 from Goddard Space Flight Center, Nov. 1970.

7. S. Mikamo, K. Mizutani, and K. Mori, "On Some Problems of Cosmic Ray Muons and Postulated Particles," INS Report 160, Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo, Japan, Nov. 1970.

8. J. D. Bjorken, S. Paksava, W. Simmons, S. F. Tuan, Phys. Rev. 184 (1969) 1345.

9. P. H. Barrett, L. M. Bollinger, G. Cocconi, Y. Eisenberg, and K. Grisen, Rev. Mod. Phys. 24 (1952) 133.

10. M. G. K. Menon and P. V. Ramana Murthy, Progress in Elementary Particle and Cosmic Ray Physics 9 (1967) 163.

11. P. J. Hayman and A. W. Wolfendale, Proc. Phys. Society 80 (1962) 710.

Table 1

Results of fits. The parameters apply to the formula given in the text. The units of D are $10^{-8}/cm^2$-sr-s-TeV. The conventional model (fits I and III) requires x=0. The absolute normalization consisted of including the known integral of particles above 1 TeV in the vertical with a 30% error. The quality of the fits is good. The errors given on D are statistical only; a 20% uncertainty should be added for possible systematic normalization error.

Fit	γ	C	D	x	Normalization constraint
I	2.60 ± 0.05	1.24 ± 0.05	8.09 ± 0.04	0	No
II	2.63 ± 0.05	1.24 ± 0.05	7.36 ± 0.11	0.053 ± 0.070	No
III	2.62 ± 0.05	1.24 ± 0.05	7.97 ± 0.04	0	Yes
IV	2.57 ± 0.06	1.24 ± 0.05	8.77 ± 0.06	-0.030 ± 0.023	Yes

Figure Captions

1. Schematic of apparatus. A, B, and C are scintillation counter hodoscopes, M is a 30 kG-m airgap magnet, and 1-6 are optical spark chambers. Mirrors to give a 90° stereo view of each chamber are not shown, nor is the 70 mm camera which views from a distance of 20 meters.

2. Measurements of the bend angle of tracks when the magnet was off. a) 12 GeV μ^+ from the Stanford Linear Accelerator at a zenith angle of 90°. b) Atmospheric muons with $p > 4$ GeV, selected by a Cerenkov counter, with a zenith angle of 60°. The curves represent calculations of the resolution based on completely independent knowledge of the measurement errors. Multiple scattering, which has not been included in the calculations, affects the width of the curves only slightly.

3. Spectra of the quantity $k = 1/p$ for different regions of zenith angle covering the range of our experiment. k is used instead of p because its error is symmetric even when large. The horizontal bars indicate the average error in k for that angular range. The solid curves are from an overall fit to the conventional model with an absolute normalization constraint. The relative amount in each angular region is a prediction of the model. The experimental resolution has been folded into the theory.

4. Angular distribution of atmospheric muons above 1 TeV.
a) The solid curve is the best fit to the conventional model of pion and kaon decay, using all our data above 0.3 TeV with an

absolute normalization constraint from other experiments represented by the cross. Our data, the vertical point, and the curves are absolutely normalized. The Utah data are from their smallest depth (2400 hg/cm^2) and represent a slightly lower energy than our experiment. The Utah points have been slightly shifted in absolute normalization so that they can be directly compared with the theoretical curves (see text for explanation of how Utah data were plotted.) The parameter x measures the ratio of anomalous muons to pions at production.

b) The corrections which were applied to our raw data to get the points in (a). The irregularities in the geometrical acceptance are due to the particular choice of triple coincidences. The resolution corrections were calculated on the basis of the momentum spectra of the conventional model fit.

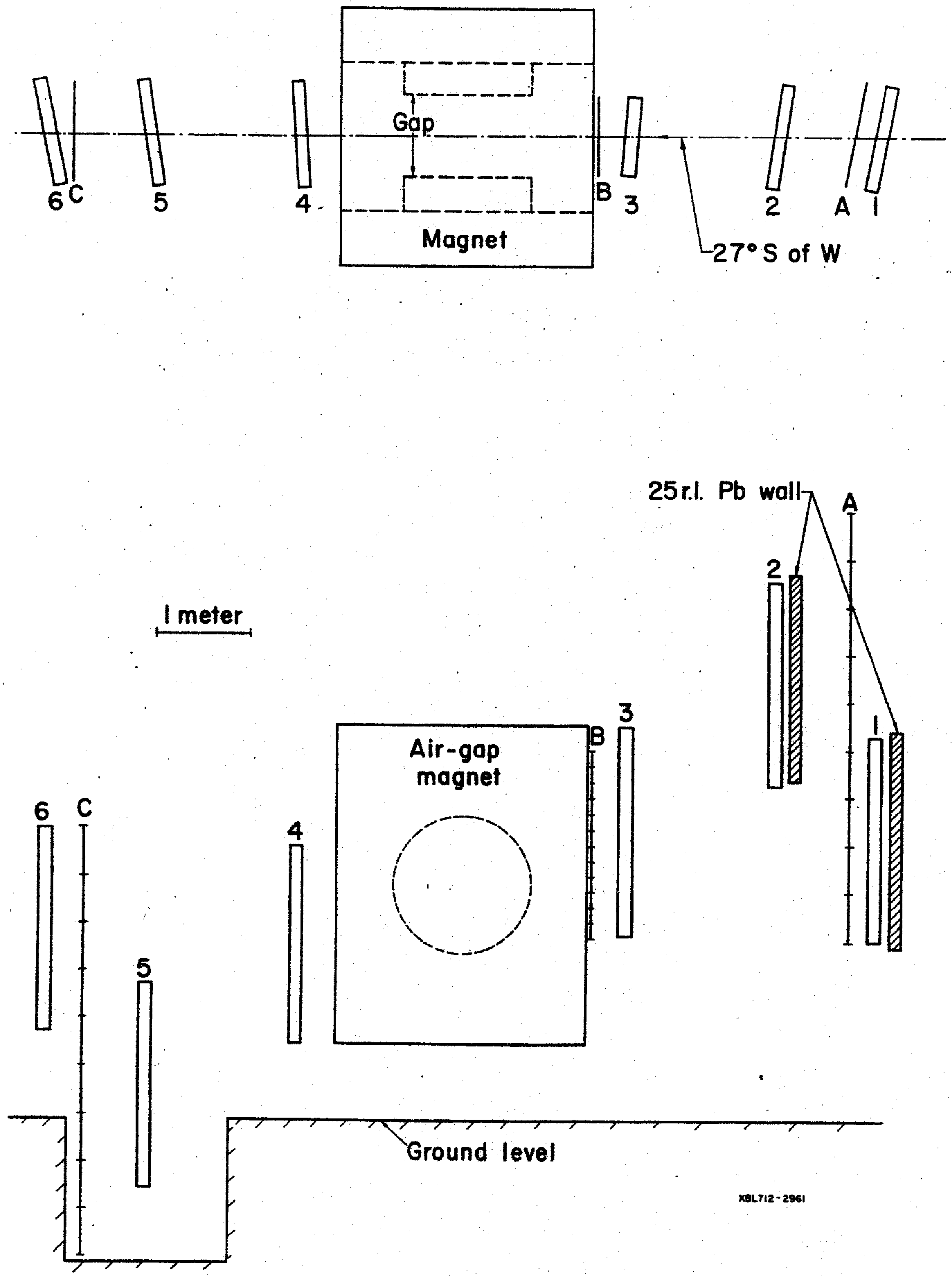
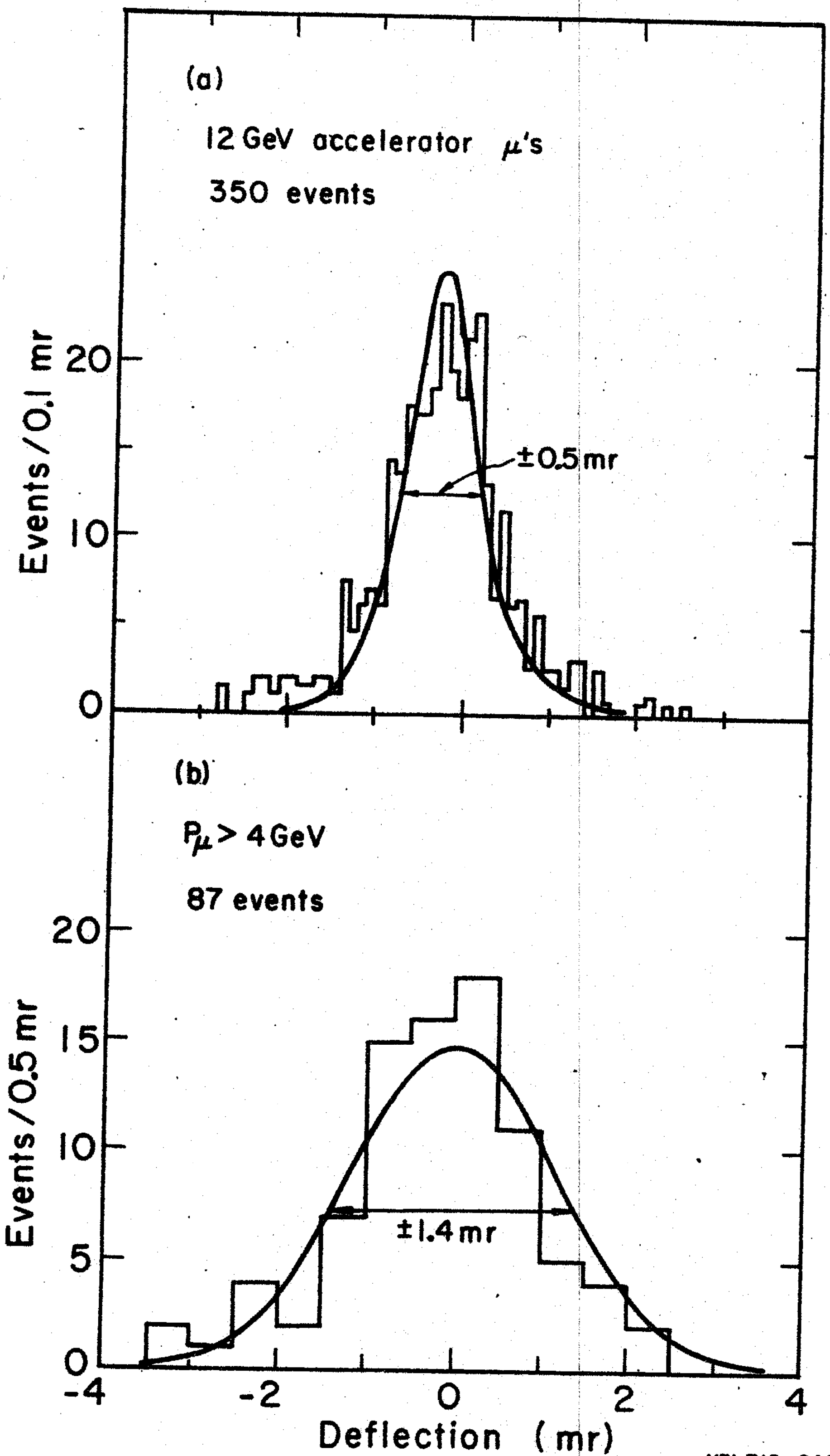

Gap
Magnet
6
C
5
4
B
3
2
A
1
27° S of W
25 r.l. Pb wall
A
2
1 meter
3
B
1
Air-gap magnet
6
C
4
5
Ground level
XBL712-2961

Fig. 1



XBL712-2958

Fig. 2

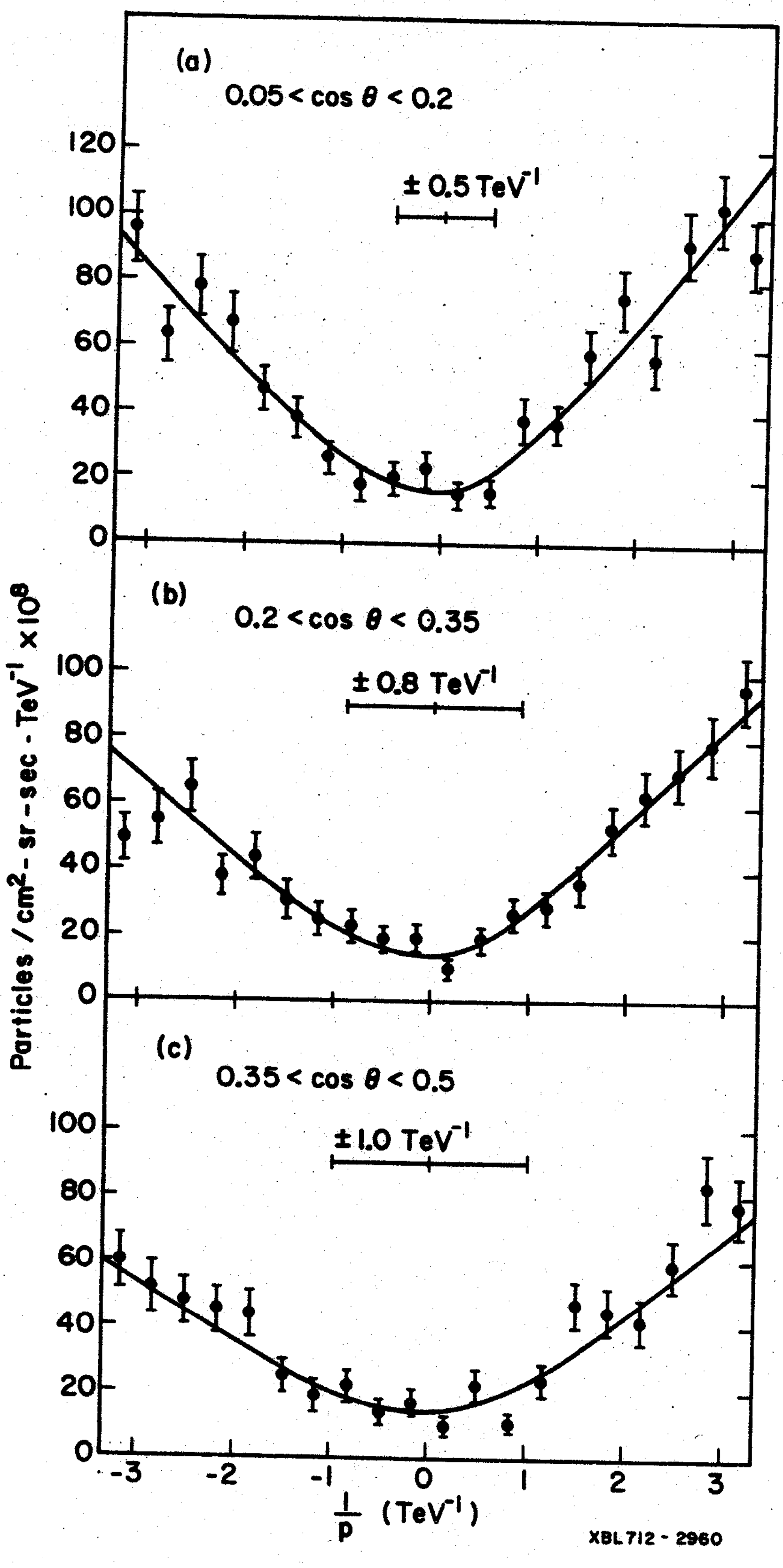

(a)
0.05 < cos θ < 0.2
± 0.5 TeV⁻¹
(b)
0.2 < cos θ < 0.35
± 0.8 TeV⁻¹
(c)
0.35 < cos θ < 0.5
± 1.0 TeV⁻¹
Particles / cm² - sr - sec - TeV⁻¹ × 10⁸
1/p (TeV⁻¹)
XBL 712 - 2960

Fig. 3

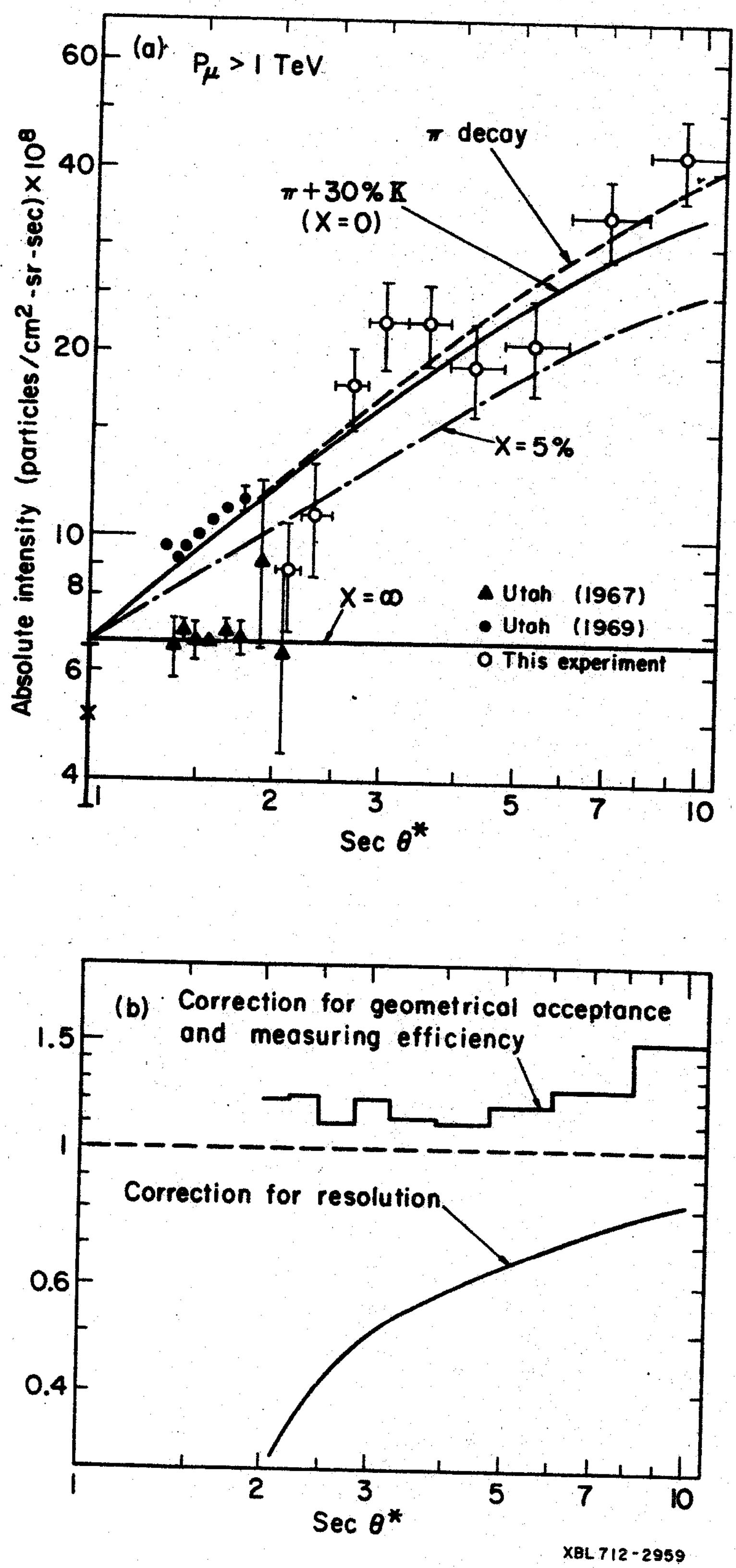

(a)
P_μ > 1 TeV
Absolute intensity (particles/cm²-sr-sec)×10⁸
π decay
π+30% K
(X=0)
X=5%
X=∞
▲ Utah (1967)
● Utah (1969)
○ This experiment
Sec θ*
(b) Correction for geometrical acceptance and measuring efficiency
Correction for resolution
Sec θ*
XBL 712-2959

Fig. 4