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Limits on the Production of Neutrino-like Particles in Proton-Nucleus Interactions From Calorimetry Measurements*

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ABSTRACT

Using calorimetric techniques, we have searched for the production of neutrino-like particles in proton-nucleus collisions. Production limits for different parameterizations of the cross section for these particles are given. Charm production cross section limits imposed by the data are also discussed.

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We report here an experiment to search for the production of neutral, weakly-interacting particles in hadron-nucleus interactions. A search for such neutrino-like objects is an interesting experiment in its own right, but there do exist theoretical speculations on the nature of such objects.[1] One manifestation of production of these particles would be a low energy tail on the measured energy distribution for protons incident on a hadron calorimeter[2] due to energy lost to neutrino-like particles[3,4] which leave the calorimeter. Muons produced in the hadronic shower would also have this signature, but in what follows we are limiting ourselves to events without identifiable muons in the final state. A calorimetry search is sensitive to the direct production of weakly interacting particles over a wide and previously unexplored kinematic range. More specifically, particles with lifetimes longer than $\approx 10^{-9}$ secs and interaction cross sections smaller than 1% of the typical hadronic cross section will be observable with good efficiency. Clearly, this type of search is sensitive to the production of prompt neutrinos,[5] the only known particle satisfying the requirements put forth above.

In addition the experiment is sensitive to new states that are produced copiously in hadronic interactions, have typical decay paths that are short compared to their absorption lengths, and decay with the emission of neutrinos. Hadrons with heavy quark constituents, i.e. charm and naked bottom states, are known examples of such states.

The experiment was performed in the Fermilab N5 hadron beam[6] using 400 GeV diffracted protons. A system of 4 x-y PWC's and a magnetic dipole providing a 16 mr horizontal bend determined the momentum to 0.5% and vertex position to 0.3 mm for each beam particle. The detection apparatus, located in Lab E directly upstream of the 15' bubble chamber, consisted of a fine-grained iron target-calorimeter followed by a magnetized steel toroidal spectrometer for momentum analysis of produced muons. The main purpose of the calorimeter in this experiment was to search for missing energy in association with the muons.[7] In this paper, however, we limit ourselves to the results obtained with the calorimeter alone by using the relatively small number of calibration triggers (i.e. random proton interactions without any muon requirement).

The calorimeter[8] shown in plan view in Fig. 1 consisted of two sections. The upstream portion consisted of twenty 76 x 76 x 3.81 cm^3 steel plates followed by twenty-five 76 x 76 x 5 cm^3 plates. Mounted behind each plate was a plastic scintillator for energy measurement. Each counter was viewed by a 6342A phototube with an amplified (x40) and an unamplified output. The performance of these counters was monitored by LED's and a light flasher system.[9] The downstream portion consisted of ten 122 x 114 x 10 cm^3 steel plates with four 122 x 28 x 1.2 cm^3 plastic scintillators behind each plate. This portion was monitored by LED's only.

The beam particle trigger for the experiment required a coincidence of signals from counters B0, B1, B2, and no HALO signal, which vetoed particles outside of a 6 cm square hole. This HALO counter was protected from "albedo"[10] (backscatter) from the interaction in the calorimeter by a 30 cm thick steel plate with a 6 cm square hole. The trigger also required that the particle interact near the front of the calorimeter by demanding at least 20 GeV be deposited in the first 38 cm of the calorimeter, and to be unaccompanied by additional beam within 95 nanoseconds before and after the triggering particle.

The constants relating the counter pulse height to the number of particles in the counter were obtained from a special run with beam muons passed through the calorimeter. The resulting constants in the upstream portion were adjusted from these muon values by requiring consistency in the shower profile for primary proton interactions at various depths in the calorimeter. These adjustments were typically in the range of a few percent.

The accepted events were required to pass several cuts designed to eliminate systematic effects on the measured energy due to upstream interactions, anomalously large albedo, or exceptionally long hadronic showers. Events with muons were eliminated from the sample by requiring that less than 5 planes in the downstream calorimeter (after 2 m of steel in which the hadronic shower is absorbed) show passage of a minimum ionizing particle. Large angle muons were eliminated by cuts on the pulse height in large area acrylic scintillation counters in the toroid system that follows the downstream portion of the calorimeter (see Ref. 7). The effect of all these cuts was to reduce the total data sample from 197,168 to 150,499 events.

The energy was determined by multiplying the number of minimum ionizing particles in each counter by the steel thickness preceding it and summing over all of the counters. The energy resolution, $(\Delta E)_{rms}/E$, was 3.57%. We found that we could improve the resolution further by using a weighted pulse height, meant to reduce the effects of fluctuation in the electromagnetic and hadronic shower components arising from fluctuations in the charged pion-neutral pion content in the hadronic shower. Several different algorithms were tried and the adopted one was:

$$E_i^{corr} = E_i \; (1 - \alpha(E) \; E_i)$$

where E_i, E_i^{corr} are the uncorrected and corrected energy contribution due to the i'th counter, E is the unweighted measured energy, and $\alpha(E) = 0.053/E$ is an empirically chosen function. The resolution with this correction was 3.40%.[11] The response of the calorimeter to 400 GeV protons at low intensity ($<$ 10 KHz) is shown as a dashed histogram in Fig. 2. The results of the study of the calorimeter energy response and its resolution as a function of beam energy (performed at a low beam rate) are illustrated in Fig. 3.

The bulk of the actual data taking was at a beam rate of about 300 KHz with fluctuations up to 500 KHz and we found that this high intensity caused adverse effects on the energy measurement. Two separate corrections were applied to the data to overcome this. The first compensated for the residual pulse height from beam particles preceding the trigger. It was found that this pulse height was roughly exponential with a typical decay time of 150 nanoseconds. The data were corrected for this effect with the help of a special electronic module that kept track of all the particles entering the calorimeter during the 3μs time period before the trigger. A second correction involving the instantaneous beam rate before the event compensated for photomultiplier gain shifts caused by the high counting rate in the scintillators. The beam rate was constantly monitored in several intervals ranging from 1.5 to 320 μsecs and was recorded with each event of interest. The size of this correction reached 1.8% for the highest instantaneous rate used. The resolution at the high rates after these corrections was 3.51%.

A plot of the final energy distribution is shown in Fig. 2 with the low energy tail displayed in the insert. The lower half of the distribution gives a good fit to a Gaussian response function over the interval from 335 to 400 GeV (χ^2 of 16.51 for 13 degrees of freedom). At the lowest energies, however, the spectrum exhibits a small excess of events over the prediction from this Gaussian (plotted as dotted lines in the insert) as shown in Table I. We cannot determine whether these events originate from a new physics phenomena, or simply represent an additional nonGaussian tail in our measurement process.

Table I

Expected and observed number of low energy events

Energy	Gaussian	Data	Excess
355-360	205	191	-14
350-355	64.1	66	1.9
345-350	17.7	26	8.3
340-345	4.27	8	3.7
335-340	0.91	2	1.1
330-335	0.17	2	1.8
< 330	0.04	3	3.0

(The excess of events with large energies above that expected from a Gaussian distribution in Fig. 2 is consistent with what one would estimate from additional undetected particles striking the calorimeter at a time near that of the event.[12] These mechanisms, however, would obviously not effect the low energy part of the spectrum.) Assumption of a Gaussian distribution[13] for the measurement resolution allows us to set limits on the production of neutrino-like particles in proton interactions by assuming that the excess in Table 1 is directly attributable to these objects.

One theory requiring new particles is supersymmetry, which predicts production of a new class of hadrons with a new supersymmetric quantum number (R).[3] Standard models of these R-hadrons predict masses of about 1-2 GeV. These high mass states would then decay by emission of pions together with a "nuino" so as to conserve the R-quantum number. The weakly interacting nuino would then escape the calorimeter giving rise to an observable missing energy. Using the excess of events beyond the Gaussian, a model dependent calculation[14] yields a 95% confidence limit on the production cross section of 33 μb for a 1 GeV R-hadron and 8 μb for a 3 GeV object. This measurement would indicate that these particles (if they exist) are heavier than first believed (as mentioned in Ref. 4).

In addition to this particular calculation, one can, in a general way, set limits on the production of non-interacting particles for various production spectra. In Table II we give the 95% confidence limits

Table II

Limits in μb for the production of new particles as a function of different parametrizations for a mass of 1 MeV (2.5 GeV)

β \ α	0	2	4	6	8	10
1	1.9(1.8)	2.7(2.3)	3.5(2.7)	4.5(3.0)	5.4(3.2)	6.3(3.5)
3	1.9(1.8)	3.0(2.6)	4.4(3.3)	6.3(4.0)	8.5(4.6)	11.3(5.2)
5	1.9(1.9)	3.0(2.5)	4.5(3.3)	6.5(4.1)	8.9(4.7)	12.1(5.4)

for the total production cross section of neutrino-like particles on the assumption of $\frac{d^2\sigma}{dx_F dP_T^2} \propto (1-|x_F|)^{\alpha}\, e^{-\beta P_T}$ for various values of α and β assuming a linear A dependence for the production of 1 MeV (2.5 GeV) particles. These data can help test new models which predict new non-interacting particles.

The axion, a light pseudo-scalar boson which might be necessary in removing CP violation in QCD theories of strong interactions,[1] is also a viable candidate for detection in this experiment. If we assume that the axion is produced with the same spectra as π^o's,[15] including A dependent effects on the laboratory x distribution[16] and an $A^{2/3}$ nuclear dependence for the total axion cross section, we obtain a 95% upper limit of 110 μb. Taking $\sigma(pp \rightarrow a^o) \sim R\,\sigma(pp \rightarrow \pi^o)$, yields an 95% upper limit of $R \leq 10^{-3.1}$,[17] consistent with the measurements of Ref. 5.

An important known source of prompt neutrinos would be the production and decay of charm particles. A model dependent calculation of charm production with a maximum likelihood fit to the data yields a 95% confidence limit of 670 μb for $D\bar{D}$ production in proton nucleus interactions.[18] We have assumed a linear A dependence for the cross section with the $D\bar{D}$ pair being decay products of a ψ'' (3770) produced according to $\frac{d^2\sigma}{dx_F dP_T^2} \propto (1-|x_F|)^5\, e^{-2P_T}$. This limit is consistent with our prompt muon data.[7] If instead we take the parameterization of Ref. 5,[19] the 95% confidence limit becomes 690 μb, consistent with the measurement in Ref. 5.

In conclusion, we have searched for new neutrino-like particle production in hadronic interactions using hadron calorimetry techniques.

From these data we have set limits on possible new particle production cross sections in hadronic interactions.

It is our pleasure to thank the technical staffs of SLAC Group G and the Caltech neutrino group whose hard work and determination furthered the success of this experiment. We would especially like to acknowledge the invaluable contribution to the construction of the calorimeter of R. Coombes, D. Ouimette, D. Porat, and C. Rasmussen and the help of F. Sciulli and J. Kirkby during the formative stages of this experiment. We also acknowledge many useful conversations with G. R. Farrar. One of us (MF) would like to acknowledge the financial support of Max-Kade Foundation. Finally, we would like to thank the administrative, operations, and service organizations of the Fermi National Accelerator Laboratory for their support in this endeavor.

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2. For a complete discussion of hadron calorimetry, see Proceedings of the Calorimeter Workshop, M. Atac, editor, Fermilab, May 1975.

3. G. R. Farrar and P. Fayet, Phys. Lett. 76B (1978) 575.

4. G. R. Farrar and P. Fayet, Phys. Lett. 79B (1978) 442.

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6. J. Lach and S. Pruss, Fermilab Note TM-285.

7. B. C. Barish et al., Caltech Report CALT 68-655 and Proceedings of the Third International Conference at Vanderbilt University, March 1978; B. C. Barish et al., Proceedings of the Bartol Research Foundation Workshop on Charm Production and Lifetimes, October 1978.

8. For a more detailed discussion of the calorimeter and its calibration see J. P. Dishaw, Ph.D. thesis, Stanford University (1979).

9. This system consisted of a Xenon Co. spark gap light flasher which was fanned out to the counters by a fiber optic array. The flasher was also viewed by three reference tubes for calibration. Two of the reference tubes also viewed an Americium source imbedded in NaI(Tl) crystals for monitoring the reference tube gain. This system provides long term gain corrections for the phototubes.

10. G. B. Yodh et al., Proceedings of the Calorimeter Workshop, page 201, M. Atac, editor, Fermilab, May 1975.

11. This is the resolution at a low beam rate (< 10 KHz). Beam intensity effects increase this number from 3.40% to 3.51%.

12. Thus, for example, the particle overlap correction mentioned in the text assumes one proton in an occupied r.f. bucket. We estimate that roughly one-third of the events in the high side tail in Fig. 2 are due to the presence of two protons in the occupied buckets before the event. Another source of high energy events is the presence of additional undetected particles arriving at the calorimeter in or near the same r.f. bucket as the trigger particle.

13. A Gaussian background is expected if the calorimetry measurement process is purely statistical. If the background should fall off faster than a Gaussian, then the limits quoted in the text will differ. We have studied this faster fall off by calculating the production limits assuming no background for the last four energy bins. In general this increases the limits by about 35%.

14. We have assumed (following Ref. 4) that these hadrons are produced as a composite pair of mass M (where $M = 2M_R + \Delta M$, M_R being the mass of the new hadron) and produced with the non-invariant cross section

$$\frac{d^3\sigma}{dM dx_F dP_T^2} \propto e^{-2\Delta M} (1 - |x_F|)^5 \, e^{-2P_T}.$$

We assume a linear A dependence (a factor of 4 over $A^{2/3}$ for Fe) for the production cross section and that the R-hadron decays into $\pi\pi\nu_R$ with a phase space distribution.

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16. C. Halliwell et al., Phys. Rev. Lett. 39 (1977) 1499; D. Chaney et al., Phys. Rev. Lett. 40 (1978) 71; D. Burke et al., Michigan Preprint UM-HE-78-6, April 1978 (to be published).

17. For the total π^o cross section in pp collisions, see J. Whitmore, Phys. Rep. 27C (1976) 187.

18. We have assumed equal portions of K and K^* in the D decay and have used a semileptonic branching ratio of 11%.

19. We have taken the production mechanism assumed in Ref. 5 to be

$$E \frac{d^2\sigma}{dx_F dP_T^2} \propto (1 - |x_F|)^3 \, e^{-P_T/.7}$$ for the inclusive D ($\bar{D}$) spectrum.

We include here simultaneous semileptonic decay for both D's with an 11% branching ratio and use an $A^{2/3}$ dependence of the cross section.

Figure Captions

1. Plan view of the hadron calorimeter. B0, B1, B2 and HALO are counters used in the trigger. The spark chambers between the two sections of the calorimeter are part of the muon spectrometer and were used in the analysis of the muon data of the experiment.

2. Final calorimeter energy distribution for low intensity data (dashed histogram) and all the data (solid histogram). The insert shows the low energy region expanded. The dotted line in the insert is the prediction from the Gaussian distribution.

3. Calorimeter response (closed circles) and its energy resolution (open circles) vs. beam energy. The total response of the calorimeter rises with energy like $E^{1.00\pm.01}$. The resolution falls like $E^{-.50\pm.03}$, consistent with a statistical width.

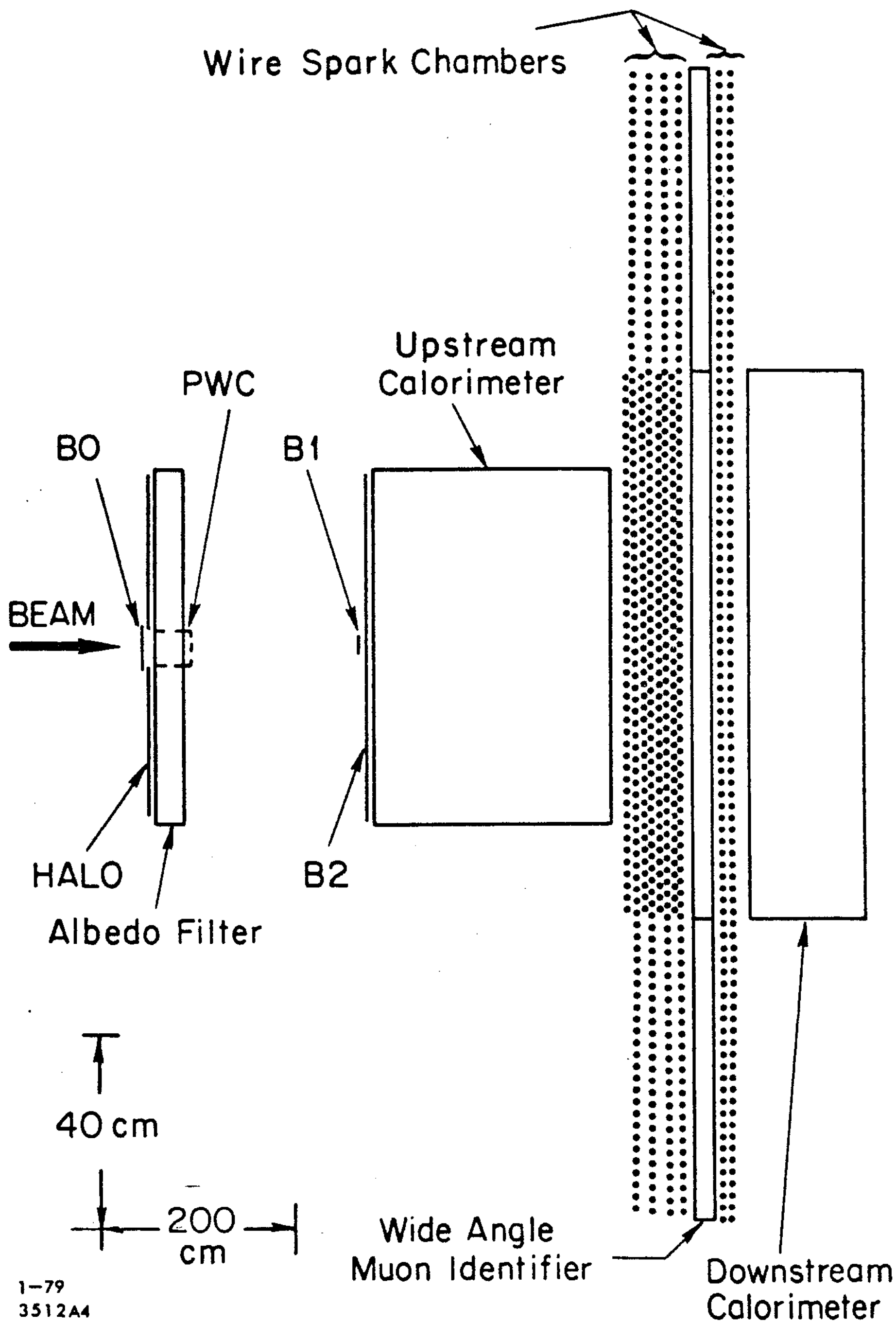
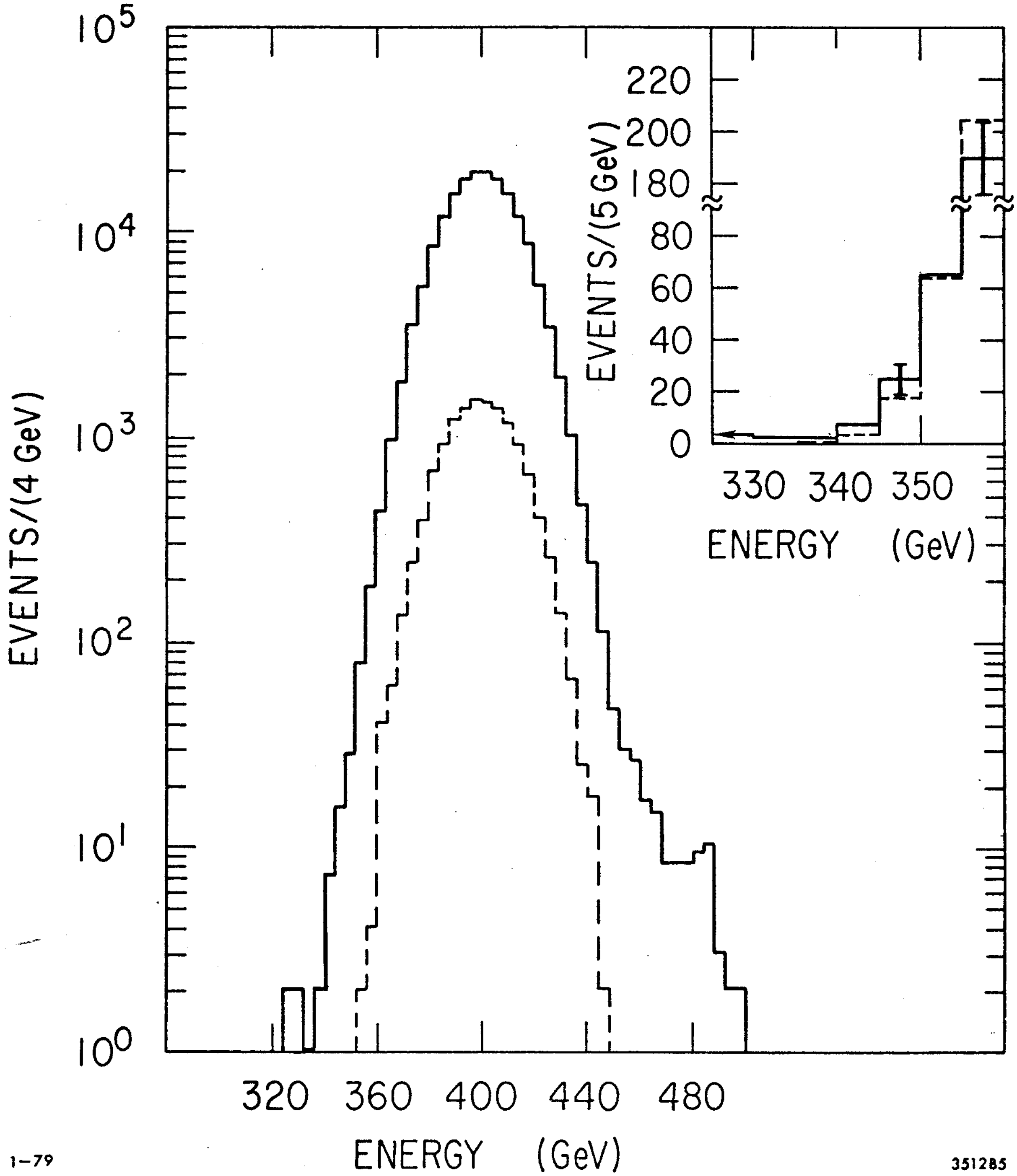
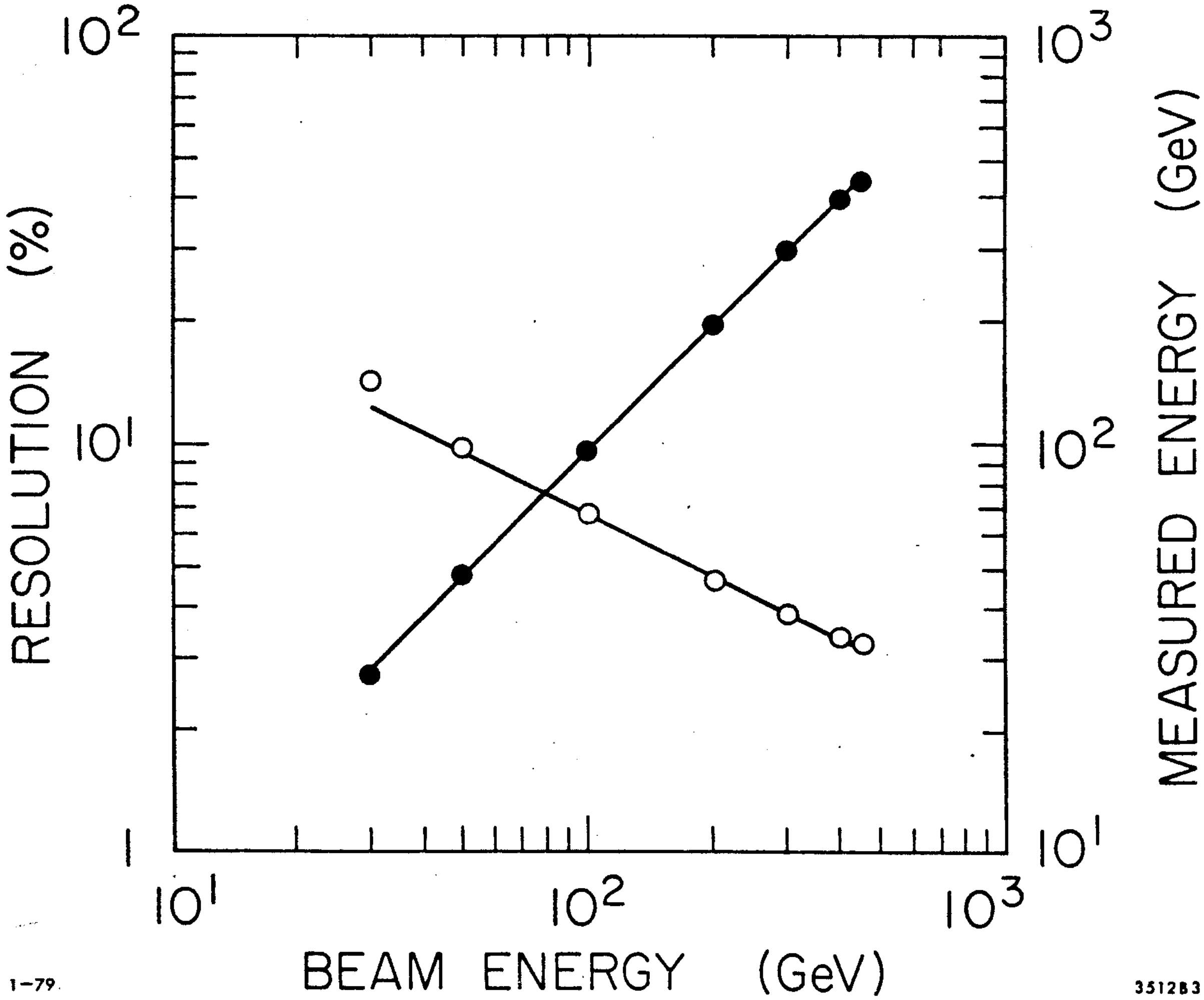

Wire Spark Chambers
Upstream
Calorimeter
PWC
B0
B1
BEAM
HALO
B2
Albedo Filter
40 cm
200
cm
Wide Angle
Muon Identifier
Downstream
Calorimeter
1-79
3512A4

Fig. 1



10^5
10^4
10^3
10^2
10^1
10^0
EVENTS/(4 GeV)
320 360 400 440 480
ENERGY (GeV)
220
200
180
80
60
40
20
0
EVENTS/(5 GeV)
330 340 350
ENERGY (GeV)
1-79
351285

Fig. 2



10²
10¹
1
RESOLUTION (%)
10³
10²
10¹
MEASURED ENERGY (GeV)
10¹
10²
10³
BEAM ENERGY (GeV)
1-79
3512B3

Fig. 3