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EXCESS MUONS AND NEW RESULTS IN ψ PHOTOPRODUCTION*

R. L. Anderson†
Stanford University, Stanford, CA 94305

INTRODUCTION

I will discuss new results from SLAC, which have been obtained by the Wisconsin-Bonn-SLAC collaboration this last fall. This run was a natural extension of our run last winter that followed closely after the discovery of the J or ψ particles. Because of the close relationship between the two runs, I would like to review briefly the results of the first run.[1]

The measurements of ψ and ψ' photoproduction were first made by observing the leptonic decay modes,

$$\gamma + p \to \psi(\text{or } \psi') + p$$
$$\hookrightarrow \ell^+\ell^- .$$

The 8 and 20 GeV/c SLAC spectrometers were used to detect simultaneously the electron and muon pairs in coincidence. The experiment was very clean; however, the counting rates were low, varying from 60-70 counts/day at best to 1-2 counts/day at worst with only small backgrounds. For example, for the ψ' where the counting rate was 1-2 a day the accidental rate between the two spectrometers was 1 in ~30 days. If one requires a reconstruction of the ψ mass from the hodoscope information, one would obtain an accidental rate of 1 in ~200 days. The hodoscopes were only used to verify that we were indeed detecting ψ's by monitoring the ψ mass distribution. This is a remarkable result in view of the unfavorable SLAC duty cycle where coincidence experiments are notoriously handicapped.

How the detection of ψ production is so favorable comes about as follows. The high mass of the ψ causes its two body decay products to appear at large $p_\perp$ namely,

$$p_\perp(e \text{ or } \mu) \sim \frac{M_\psi}{2} \sim 1.6 \text{ GeV} .$$

Since hadronic backgrounds fall as

$$Y_{\pi's} \sim e^{-6p_\perp},$$

they represent a relatively small background. In fact even for single arm lepton rates in the spectrometer at $p_\perp \sim 1.6$ GeV/c, 60-70% of the direct leptons are solely due to the ψ particle. Not only do most of the direct leptons come from ψ decay but their signal is only a factor 750 down from the inclusive pion

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yield at $p_\perp \sim 1.6$ GeV/c (unlike hadron production of ψ's).

The experimental layout for the two runs was the same except for a modification of the target area. Figure 1 shows a plan view of End Station A, showing the three spectrometers. For coincidence work, the two spectrometers (8 and 20) were set symmetrically in $p_\perp$ on each side of the beam line. Also the spectrometers were instrumented almost identically to detect simultaneously electrons and muons. Both had a gas Cerenkov counter, shower counter with preradiator, muon 3-counter telescope, and hodoscopes allowing reconstruction of the ψ mass with a $\sigma \sim 6$ MeV. Figure 2 shows the counters in the 20 GeV/c spectrometer as instrumented for the second run. Here a second threshold Cerenkov counter was added allowing one to separate electrons, muons, and pions by Cerenkov radiation. In the 8 GeV/c spectrometer there is only room for one Cerenkov counter, and it was unchanged.

The results and conclusions of the first run that are pertinent to the fall run are:

1. An angular distribution was obtained at 19 GeV giving a slope parameter parameter of $b = 2.9$ GeV/c^{-2}.
2. A mass search was made for charmed particles in the range $1.8 < M < 2.4$ GeV for $D \to \pi\pi$, πk, $p\bar{p}$, ... giving a negative result:
$$\frac{BR\sigma_D}{\sigma_T(\gamma N)} < 10^{-3} .$$
3. Employing the VDM and the optical theorem and assuming ReA/ImA = 0, we obtained the indirect result:
$$\sigma(\psi \text{ or } \psi', N) = 1 \text{ mb} ,$$
which indicated the ψ's were hadrons.
4. The s dependence was determined (Fig. 3). Figure 3 also shows the Cornell point at 11.3 GeV and the FNAL point at 100 GeV. The cross section has a very unusual threshold behavior. Although the Cornell point is plotted at 11.3 GeV, they reported that they observe no appreciable change in $d\sigma/dt|_{\theta=0}$ from 9.3 GeV to 11.8 GeV. This suggests with the rise in the cross section at higher energies as measured at SLAC that there might be a pseudo threshold at ~13 GeV corresponding to charm threshold. The increase in the elastic cross section is merely a reflection of the inelastic channel where the D particles are being produced.
5. Inelastic ψ photoproduction was found to be small (<20%)
$$\gamma p \to \psi p + X .$$
If one estimates the inelastic ψN cross section associated with the elastic ψN cross section by the optical theorem and assuming by VDM that the ratio of elastic to inelastic photoproduction is the same, one finds that the elastic ψ production constitutes only ~1% of the expected cross section. It is speculated that the inelastic cross section involves the production of D mesons.
6. Finally, we found that we could detect ψ photoproduction by a single arm technique. This, of course, has the advantage of a much higher counting rate since the counting rate loss due to the coincidence requirement is absent. Figure 4 shows a result obtained by measuring direct electrons. $p_\perp$ is varied by varying the spectrometer angle. We see that at $p_\perp \sim 1.6$ GeV/c, 60-70%

of the direct electrons come from ψ decay. Such a technique accepts ψ's produced over a range of s and t. However, this is unimportant for certain measurements.

GOALS OF THE FALL RUN

The goals of the fall experiment are suggested by the unanswered questions of our first run and from our experience in measuring ψ's; for example, our success in demonstrating that ψ's could be detected by the single arm technique, which allows much higher counting rates. They were as follows:

1. Determine directly $\sigma(\psi N)$ by determining the A dependence of the diffractive photoproduction cross section on Be and Ta.
2. Study the energy dependence of ψ photoproduction verifying the large change in magnitude between the Cornell measurements at 11 GeV and the SLAC measurements above 13 GeV and looking if possible for a pseudo-threshold corresponding to charm threshold at ~13 GeV.
3. Look for prompt leptons in photoproduction, in particular looking for a threshold effect to see if they might be due to the leptonic decays of the D mesons.
4. Continue the double arm program (this will not be reported here).

From our VDM prediction we expect $\sigma(\psi N) \sim 1$ mb. The required accuracy in the A dependence to measure $\sigma(\psi N)$ is ~7%/mb. The tantalum target would have to be very thin in grams because of its high radiation length. Thus the double arm coincident method is not feasible. However, the single arm technique is ideally suited for this measurement. Also the s dependence near threshold cannot be done with the double arm method because the counting rates are prohibitively low. However, for a broad brush determination of the variation of the cross section the single arm method is adequate.

APPARATUS

Although we had verified that photoproduced ψ's could be measured by a single arm spectrometer by observing prompt electrons, we proceeded to make our measurements with muons. Bethe-Heitler production of muons is down by a factor of 3 and the extrapolations required to eliminate normal lepton sources were simpler. With muons the only sources beside Bethe-Heitler production are muons from π decay. Muons from π decay can be determined by placing absorbers near the production target, translating the absorbers and extrapolating the resulting measurements to zero decay path. Bethe-Heitler production can be calculated.

The layout of the target area is shown in Fig. 5. The spectrometers were unchanged from the first run except for the addition of the second Cerenkov counter of the 20 GeV/c spectrometer as shown in Fig. 2. The target area was instrumented with a solid target assembly and a hadron absorber allowing one to detect prompt muons in either the 8 or 20 GeV/c spectrometers. The hadron absorber and target were designed to allow the full SLAC electron beam to be run within 1/2 inch of the hadron filter.

A variety of remotely selectable solid targets was available, including

Tantalum, Aluminum, 0.5", 2.0" and 4.0" thick Beryllium, and null targets. The targets were enclosed in a narrow helium-filled scattering chamber with thin aluminum windows. The chamber was made long enough to keep the beam entry and exit windows out of the field of view of the spectrometers. The entire target assembly could be remotely moved from side to side in order to reduce the target material traversed by a particle originating along the beam path as it traveled toward one spectrometer or the other. Since the spectrometers were on opposite sides of the beam line, the target position could only be optimized for one spectrometer at a time. Care was taken to ensure that the beam was fully within the target and not spilling over the edge. The target selection and coordinate were recorded by the computer.

A helium-filled duct downstream from the target reduced room background from the beam. Photon beams were stopped by a secondary emission quantameter (SEQ) within a concrete shielding enclosure at the rear of the end station, which measured the total energy in the beam. Electron beams passed through the end station to a remote shielded beam dump, and were measured by the SLAC integrating toroid monitors upstream of the target. One toroid, ahead of the photon beam production target, was also useful for monitoring the photon beams. The 1.6 GeV/c spectrometer was set up to view the target under fixed conditions and provided a stable relative monitor.

The variable thick iron muon filter could be adjusted to stop all particles except muons from entering the spectrometers. The filters were suspended from a frame which could rotate about the target center and translate radially from the target center in the horizontal plane. The filters were composed of 3 or 6 separate iron slabs (for the 20 GeV/c or 8 GeV/c spectrometers respectively), which were independently suspended from the frames and remotely retractable in any combination so that they could be completely raised above the flight paths of the relevant particles. The slabs nearest the target were faced with tungsten to increase their stopping power. The number of muons produced as a result of pion decays between the target and the iron could thus be varied by changing the flight path between the target and the filter iron, either by moving the iron sideways or by retracting the front slabs. The effective thickness of the iron between the target and spectrometer could be controlled by varying the number of slabs retracted and by varying the angle of the filters relative to the spectrometer. In one mode of operation, the filters were rotationally locked to the spectrometers so that the relative angle could not change as the spectrometer angle was varied. The slab combinations, positions, and angles were recorded by the computer.

The on-line computer, an SDS9300, recorded on tape the settings and status of the equipment, event-by-event data, scaler readings, and beam monitors. It also provided control of the spectrometers, monitored rates, analyzed samples of the data and created paper and microfilm records of the data. Subsets of the data were transferred to the SLAC computation facility for additional analysis as the experiment progressed.

PROCEDURE

Figure 6 shows an iron filter attenuation curve for μ^+ and μ^- where we have adjusted the amount of iron by retracting the iron slabs one at a time. We see μ^- are more favorable than μ^+ because of K decay. As a result, we made all of our measurements with negative muons. Figure 7 shows one of the $p_\perp$ sweeps obtained for the running conditions of the A dependence measurements.

This was made with the 20 GeV spectrometer, 4" Be target, 20 GeV photon energy, and for a momentum of -9.0 GeV for the muon as it originates in the target. Mu meson Bethe-Heitler production was calculated in consultation with Paul Tsai.[2] For such sweeps we also made a separate measurement of the π spectrum by removing the iron and adjusting the momentum of the spectrometer to the target momentum with the iron in place. The two dead reckoned curves are added to give the total background, which fits well at a $p_\perp \sim 1$ GeV where there is no ψ production. The solid curve is a fit as a result of a calculation. Empty target effects were negligible. Figure 8 shows the ψ yield by subtracting the background from the predicted shape. The ψ yield is determined by the value at $p_\perp \sim 1.65$ GeV/c.

ψ-NUCLEON CROSS SECTION VIA THE A-DEPENDENCE

To measure the ψ-nucleon cross section directly, photoproduction of ψ's was measured from a beryllium and a tantalum target, each of 0.3 radiation length thickness. The ψ-nucleon cross section is determined from the measured ratio of the cross sections.

Measurements were made on single muons at a $p_\perp$ of 1.65 GeV/c with the SLAC 20 GeV spectrometer. The primary peak bremsstrahlung energy was 20 GeV and the detected negative muons had a momentum of 9 GeV/c at the target.

Empty target subtractions even for tantalum were less than 5%. About 1100 events were observed from the tantalum target and about 4000 events from the beryllium target. To evaluate backgrounds, the pion fluxes were measured from the respective targets and a $p_\perp$ sweep was made for the muon flux to determine the backgrounds from sources other than ψ-decays. Figure 7 shows the detected muons fitted for direct Bethe-Heitler production and ψ-decay. At a $p_\perp$ of 1.65 GeV, 11% arise from pion decay, 20% arise from Bethe-Heitler production, and 69% are from ψ-decay.[2]

The raw measured ratio $|\mu(\mathrm{Be})/\mu(\mathrm{Ta})|_{raw} = 1.19 \pm .04$. The measured ratio of pions from the targets was $1.18 \pm .02$ and hence the ratio for background muons arising from pion decay should also be $1.18 \pm .07$. The calculated ratio for Bethe-Heitler production is $1.03 \pm .02$.

If the raw ratio is corrected for the background, the corrected ratio $|\mu(\mathrm{Be})/\mu(\mathrm{Ta})|_{\psi's} = 1.25 \pm .055$. Nuclear physics corrections to the ratio are 6% arising from Pauli suppression, 3% from coherent production and -1% from the Fermi-momentum corrections to the cross section for ψ-production. The ratio corrected for nuclear physics is then

$$|\mu\mathrm{Be}/\mu\mathrm{Ta}|_{\psi}^{\mathrm{Corr}} = 1.17 \pm .055 \ .$$

To determine the ψ-nucleon cross section from this result, we used the standard model with $A_{eff/A} = 1-\delta/A$

$$\frac{\delta}{A} = \frac{9}{16\pi}\left(\frac{\sigma_{\psi N}}{r_o^2}\right)A^{1/3} = 1.33 \cdot 10^{-2}\ \sigma_{\psi N}\ A^{1/3}\ (\mathrm{mb})$$

yielding

$$\boxed{\begin{array}{l}\sigma_{\psi N} = 2.75 \pm 0.90 \text{ mb} \\ \text{statistical error only.}\end{array}}$$

The estimated systematic error is ~ ± 0.5 mb.

Therefore ψ-nucleon cross section is significantly different from zero mbs. Our result agrees with the value obtained from Vector Dominance arguments using the photoproduction cross section and the value of the photon-ψ coupling obtained from colliding beams.

ENERGY-DEPENDENCE OF THE CROSS SECTION

To measure the production of ψ's, we made sweeps in $p_\perp$ with the 8 GeV spectrometer at 10 GeV, 12 GeV, 14 GeV, and 16 GeV maximum bremsstrahlung energies. The detected momentum at the target was -5.5 GeV/c for a muon. $p_\perp$ was varied by varying the detection angle. Both the pion and the muon spectra were measured in separate sweeps with and without a hadron filter.

Figure 9 shows the muon yields versus $p_\perp$. The pion spectra were fitted to the form: yield (pions) = $A_\pi \exp(-B_\pi p_\perp)$ (with B_π~6). The resulting spectrum for muon decay should be of the form:

$$\frac{A_\mu \, e^{-B_\pi p_\perp}}{B_\pi p_\perp} .$$

The calculated Bethe-Heitler directly produced muons have an almost identical shape. We, therefore, fitted our muon yields to the three parameter form:

$$Y_\mu = \frac{A \, e^{-Bp_\perp}}{Bp_\perp} + C(\psi\text{-shape}) .$$

The first term represents muons from pion decay and B.H. production. The values of A and B obtained were close to those that were obtained by calculation from the pion spectrum and B.H. production.

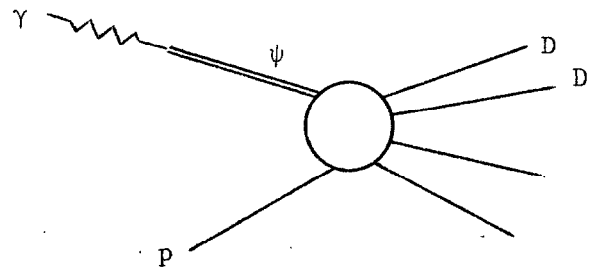
The ψ-shape was obtained from a Monte Carlo calculation. The hard lines in Fig. 9 are computer fits to the yield curves. The dotted lines show the extrapolation of the background terms.

From the values of C obtained, the cross section for ψ's was unfolded. Figure 10 shows the result of $|d\sigma/dt|_{t_{min}}$ evaluated at t_{min}. The major source of error is the value b of the slope parameter to be used for this determination. We used a value of b = 2 GeV/c^{-2}, which could be in error by a factor 1.5.

We conclude on the basis of Fig. 10 that the new measurements, the Cornell measurements, and our old SLAC measurements are all in reasonable agreement and show a substantial increase at 12 GeV. This is in line with Vector Dominance models that would expect a substantial increase in the ψ-nucleon cross section at the energy for which the charmed D particles can be produced.

EXCESS LEPTON PRODUCTION

Sivers, Townsend, and West (S.T.W.) (SLAC PUB-1636) discuss the photoproduction of D's. It is expected that a lower limit for the production of D's is given by the following diagram:



$$\sigma(\gamma p \to D's + \ldots) \simeq \alpha \frac{4\pi}{f^2_\psi} \sigma_{tot}(\psi p)$$

$$\simeq 500 \text{ nanobarns}$$

S.T.W. give $\sigma(\gamma p \to D's) \geq 300$ nbarns.

Therefore unlike the case for hadron production there exists a firm estimate of the D's produced via photoproduction. The cross section is comparatively large, being of the order of .4% of the total photoproduction cross section.

We measured "excess" muon production from a Beryllium target to see if we could detect muons produced from non-conventional (new physics) sources. In order to eliminate the muons from pion and kaon decay, measurements were made with the hadron filter at various distances from the target. These displacement curves were extrapolated to zero effective pion decay length to determine the prompt muon flux arising from sources other than decays. To make these extrapolations, we made a Monte Carlo calculation to take into account the multiple scattering effects on the input spectrum and the aperture of the spectrometer. Lateral displacement curves (Fig. 11) were taken at end point energies of 8 GeV, 12 GeV, and 20 GeV and at a $p_\perp$ of 1 GeV^2. The slopes of the lateral displacement curves were used to calibrate the effective aperture of the spectrometer so that prompt muons arising from Bethe-Heitler production could be calculated.

Results are given in Table I. The signal at 8 GeV and 12 GeV is accounted for by the prompt muons arising from Bethe-Heitler pair production. There appears to be a significant signal at 20 GeV with a μ/π ratio ~ 10^{-4}. This is similar to that observed in hadron experiments. To eliminate systematic effects, the only variable changed was the energy of the primary bremsstrahlung beam. Therefore the secondary momentum of the muons was held constant. A variation of primary energy, therefore, also corresponded to a variation in Feynman x. It is, therefore, possible to attribute the observed variation in the μ/π ratio to either the variation in Feynman x or to the variation with energy.

If all the excess muons at 20 GeV are attributed to charmed D decays, we can compare our result with model estimates. If we assume D's are produced with an integrated cross section proportional to the ψ-cross section, and with a shape

$$\frac{d\sigma}{dp^2\, dx} \alpha\, e^{-5m_\perp}(1-x)^2$$

(of course, other assumptions can be made)

$$m_\perp = \sqrt{m_D^2 + p_\perp^2}$$

then our result is $\sigma(\gamma p \to D)$ x (Branching ratio to D's) = 2 10^{-33} cm^2 at a $p_\perp$ of 1 GeV/c and a muon momentum of -5.5 GeV/c.

Estimating from theory, by combining the S.T.W. cross section with a 5% branching ratio gives $\sigma(\gamma p \to D)$ x BR $\geq$ 15 10^{-33} cm^2, a factor seven times higher than the observed value. This disagreement is uncomfortable, but it cannot be ruled out that other production spectrum assumptions would produce agreement between observation and expectation.

TABLE I. Excess Muons

E (GeV)	Total Excess/10^{15}e's	Calc B.H.	Net Excess (Total -B.H.)	Net Excess In Units of $\mu/\pi \cdot 10^5$
8	1.25 ± 0.42	1.15 ± 0.25	0.1 ± 0.5	1.4 ± 7.0
12	9.34 ± 0.87	6.90 ± 1.70	2.4 ± 2.0	4.8 ± 4.0
20	38.20 ± 2.60	14.40 ± 3.60	23.8 ± 4.4	14.0 ± 2.5

CONCLUSIONS

The measurement of the ψ meson photoproduction cross sections can be made by detecting only one of the two leptons of the leptonic decay modes with the muon preferred over the electron as the detected particle. The single arm technique accepts a range of s and t but has a much higher counting rate than the double arm coincidence method. The two methods complement each other.

The ψ-nucleon cross section has been determined by measuring the A dependence of ψ photoproduction and gives

$$\sigma(\psi N) = 2.75 \pm 0.90 \text{ mb}$$

which is in reasonable agreement with the result obtained with the use of VDM and the optical model.

The low energy data obtained at SLAC and Cornell has been verified. An increase at 12-13 GeV photon energy is observed, which agrees with the expectation of the Vector Dominance models that predict an increase in the ψ photoproduction cross section due to an increase in $\sigma(\psi N)$ at charm threshold.

We observe a significant excess lepton signal at 20 GeV photon energy with a μ/π ratio

$$\mu/\pi = 14 \pm 2.5 \times 10^{-5} .$$

No excess is observed at 8 and 12 GeV.

ACKNOWLEDGEMENT

We would like to acknowledge the invaluable assistance of Paul Tsai in the calculation of the Bethe-Heitler cross sections. We have used his computer program with a nuclear form factor more appropriate for large momentum transfer.

We also would like to thank Fred Gilman and Stanley Brodsky for useful discussions. We would like to thank W. K. H. Panofsky and the staff of the Stanford Linear Accelerator Center for their support.

REFERENCES

1. cf. R. Prepost, Lepton Photon Conference, 241 (1975).

2. Y. Tsai, Rev. Mod. Phys., 46, 815 (1974).

FIGURES

Fig. 1. Plan view of SLAC spectrometers as they were set up for detection for ψ photoproduction by the double arm coincidence method. For this experiment the target area was modified to include a hadron absorber and a variable solid target.

Fig. 2. The counters of the 20 GeV/c spectrometer. The counters in the 8 GeV/c spectrometer are very similar except there is only one threshold Cerenkov counter.

Fig. 3. $d\sigma/dt$ at $t = t_{min}$ for $\gamma p \rightarrow \psi p$. Only data before this experiment are included.

Fig. 4. Single arm electron yields as a function of transverse momentum for $p_{spect} = 6.0$ GeV and $E_o = 21.5$ GeV.

Fig. 5. Plan view of target area for single arm ψ and excess lepton experiment showing details of muon filters.

Fig. 6. Muon filter attenuation curve for positive and negative muons. All data were taken with negative muons.

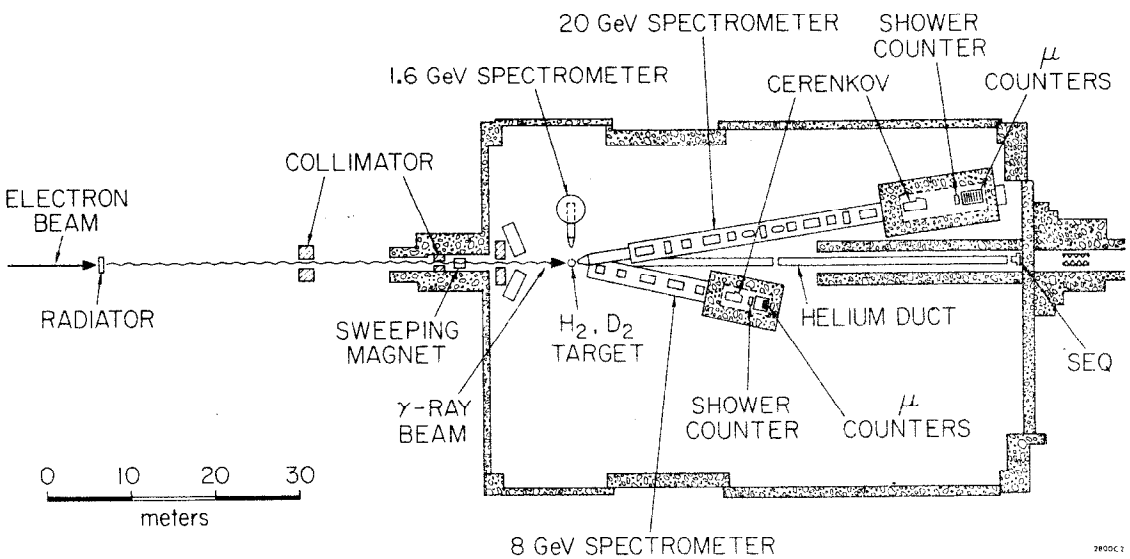
Fig. 7. Muon yield curve obtained with 20 GeV/c spectrometer from a 4-inch beryllium target used to determine the A dependence of ψ photoproduction. Photon beam was used.

Fig. 8. ψ yield obtained by subtracting background from muon yield curve including the predicted ψ shape.

Fig. 9. Muon yield curves at incident photon energies of 10, 12, 14, and 16 GeV/c for a muon momentum at the target of -5.5 GeV. Photon beam was used.

Fig. 10. Threshold behavior of $d\sigma/dt$ at $t = t_{min}$ for ψ photoproduction. Black circles are the single arm measurements of this experiment.

Fig. 11. Excess leptons at 8, 12, and 20 GeV photon energies obtained by displacing the muon filters relative to the target. Electron beam was used.



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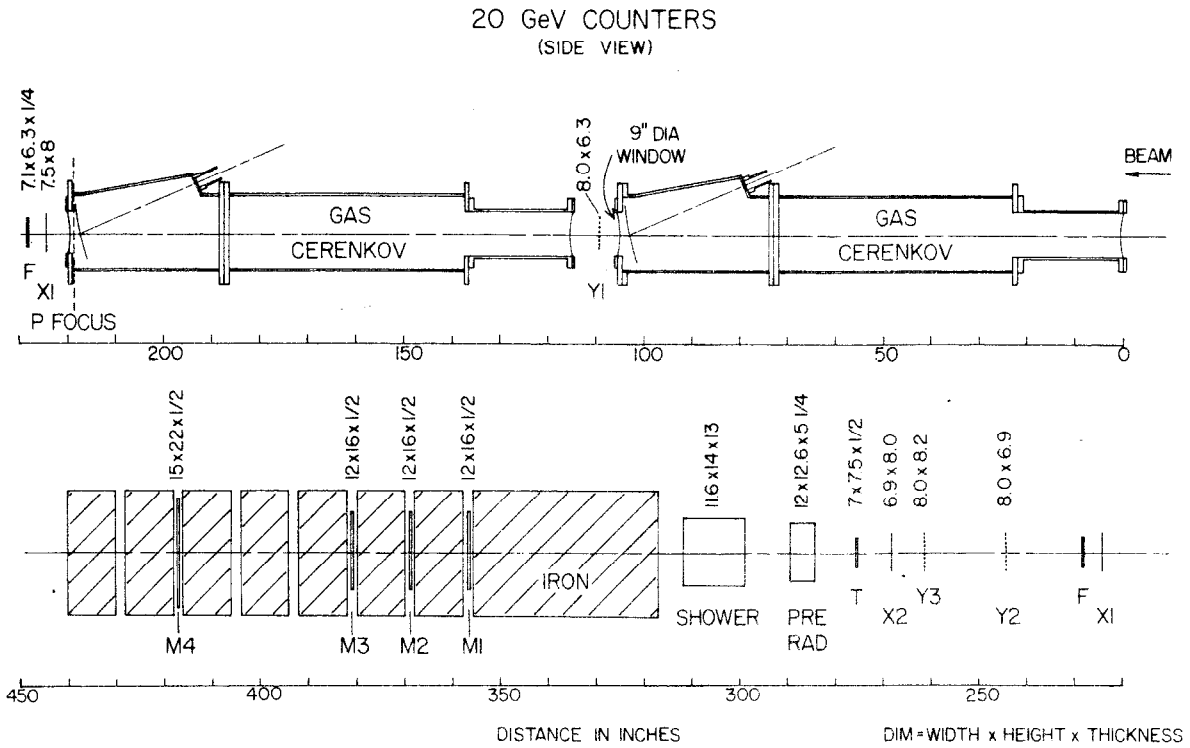

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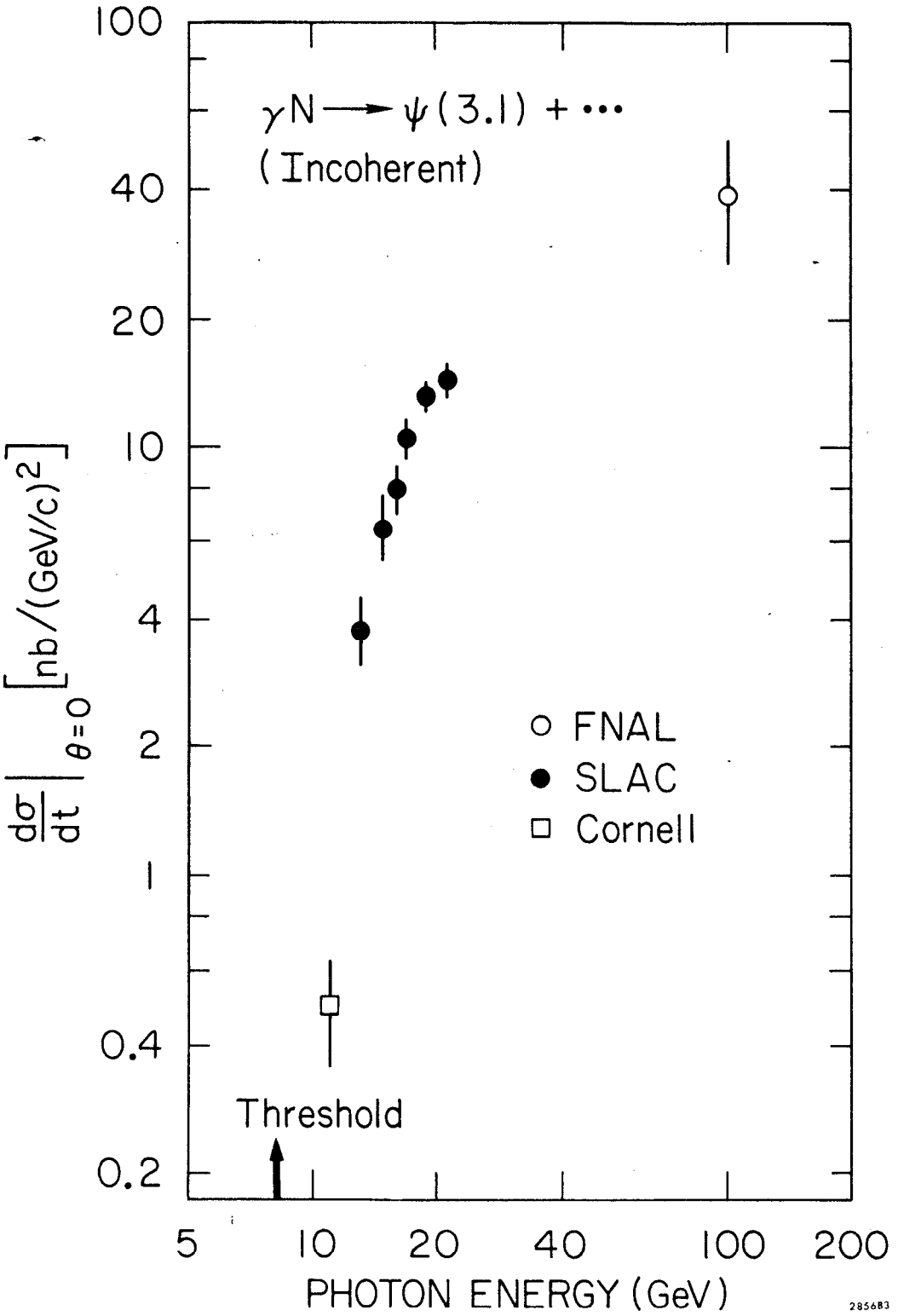

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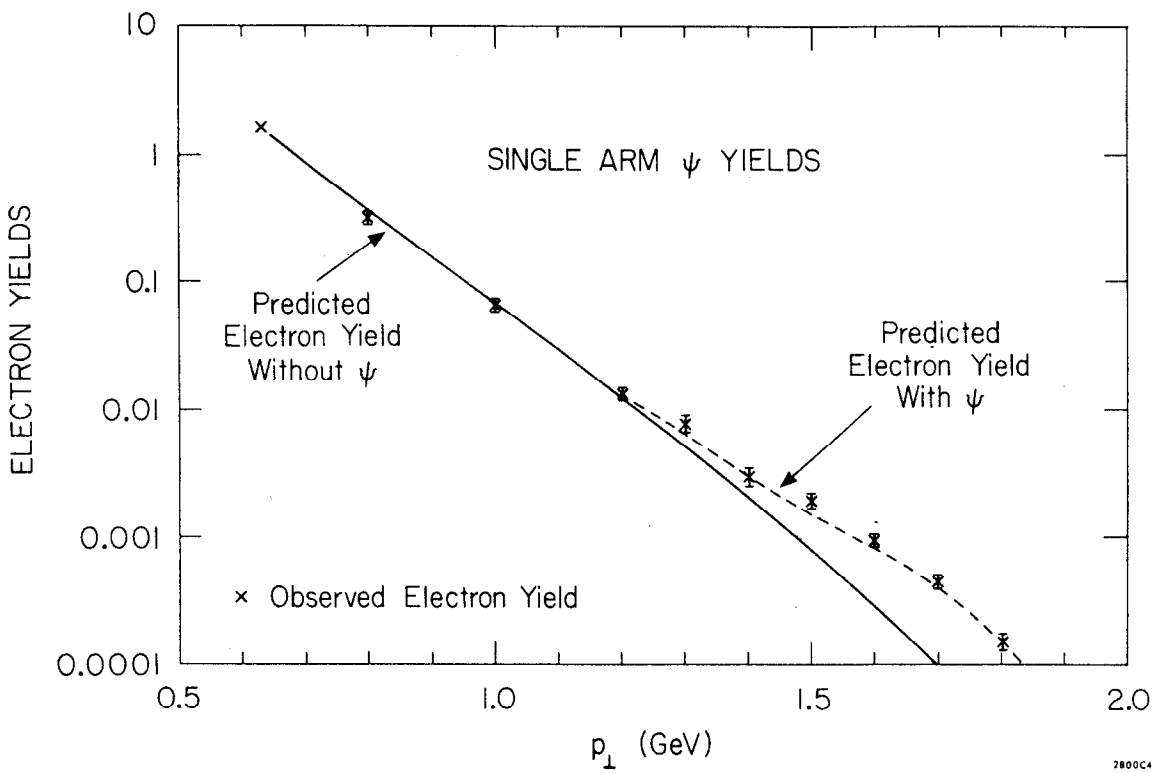

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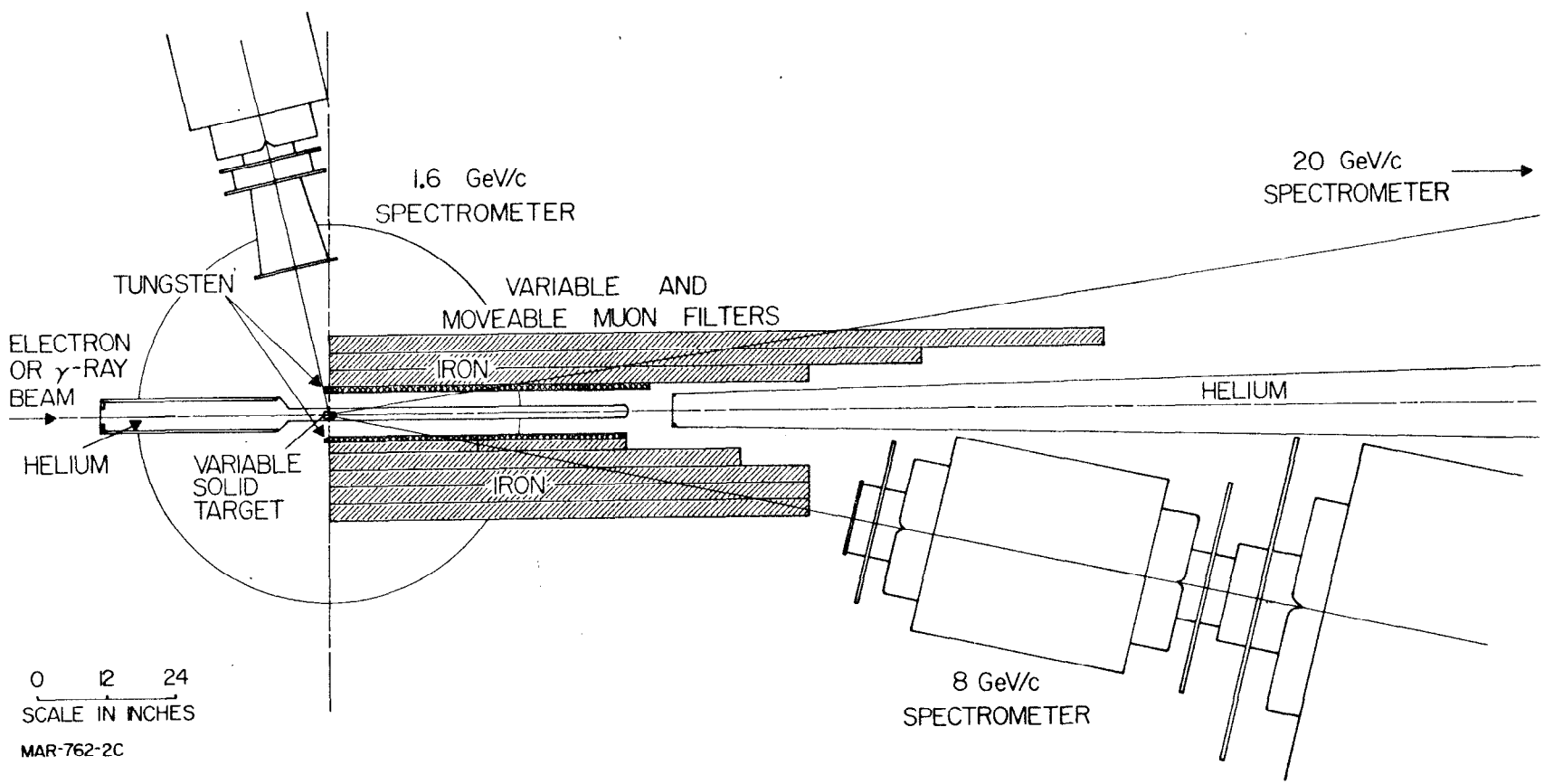

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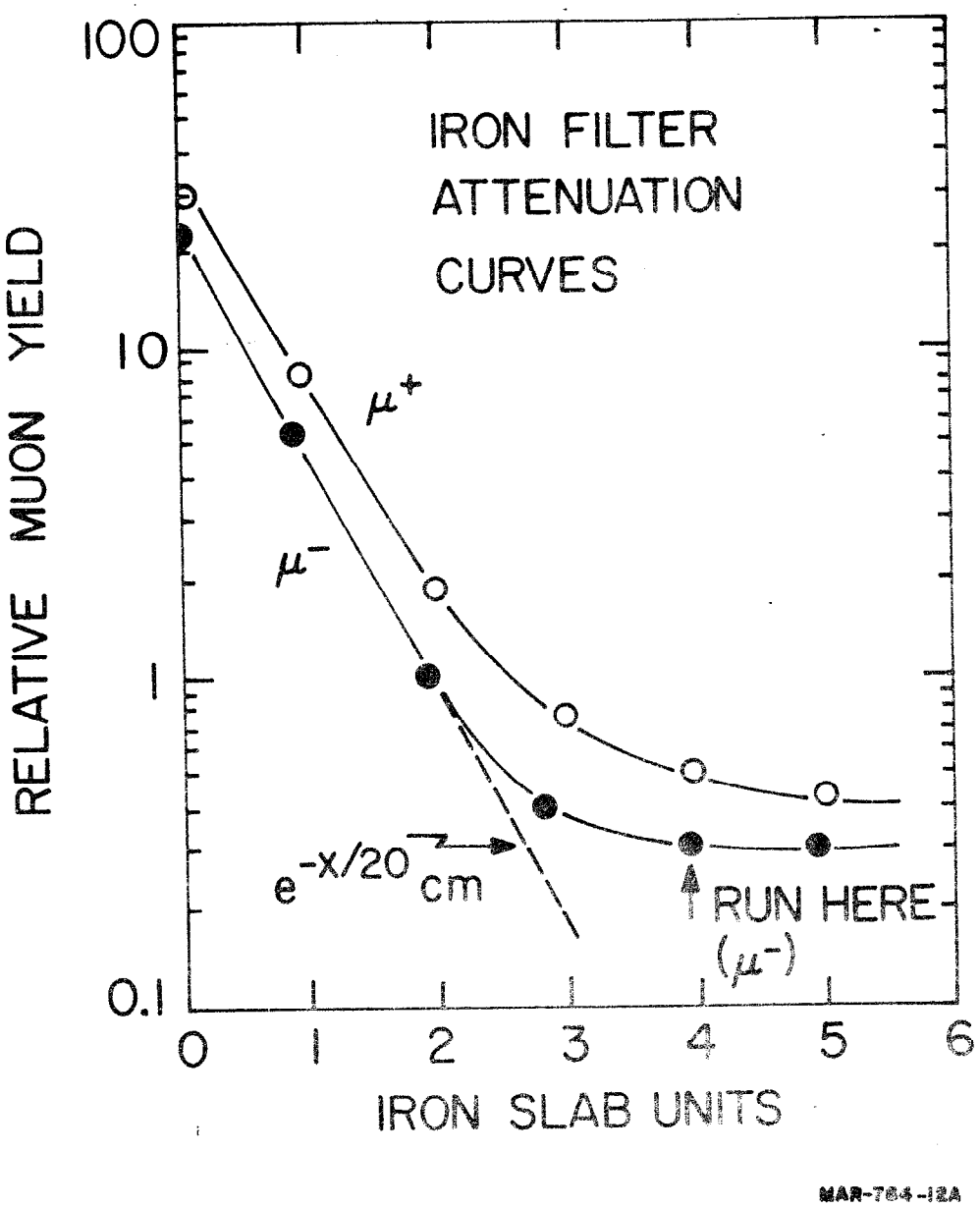

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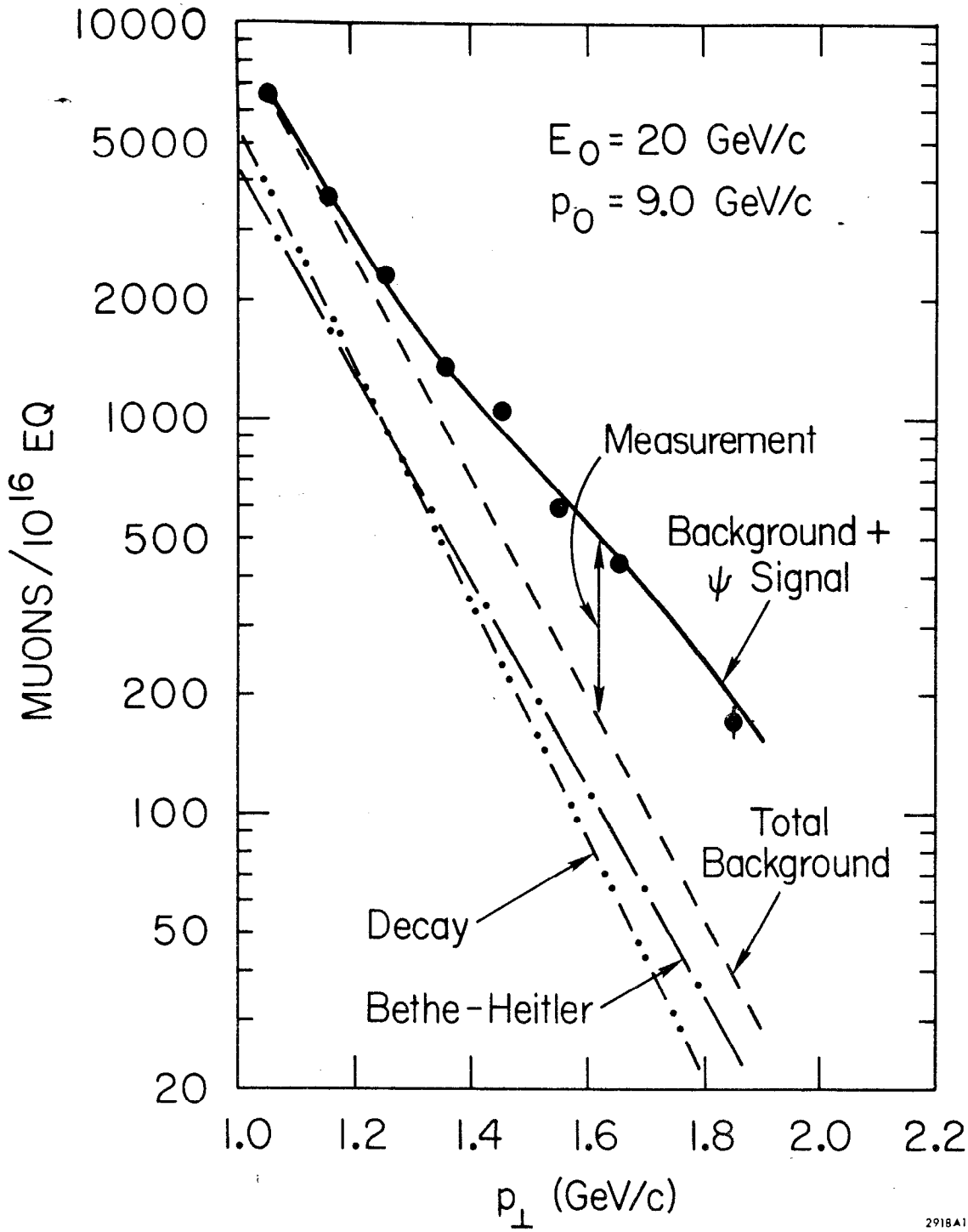

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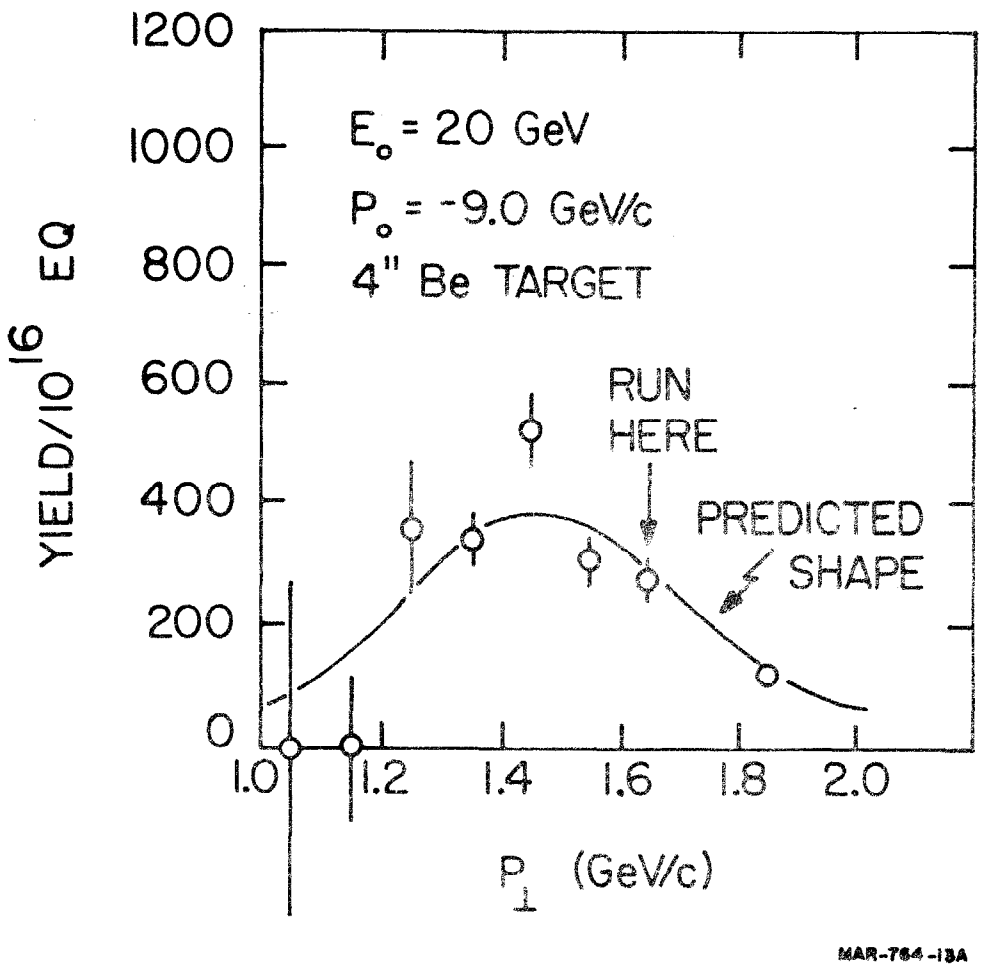

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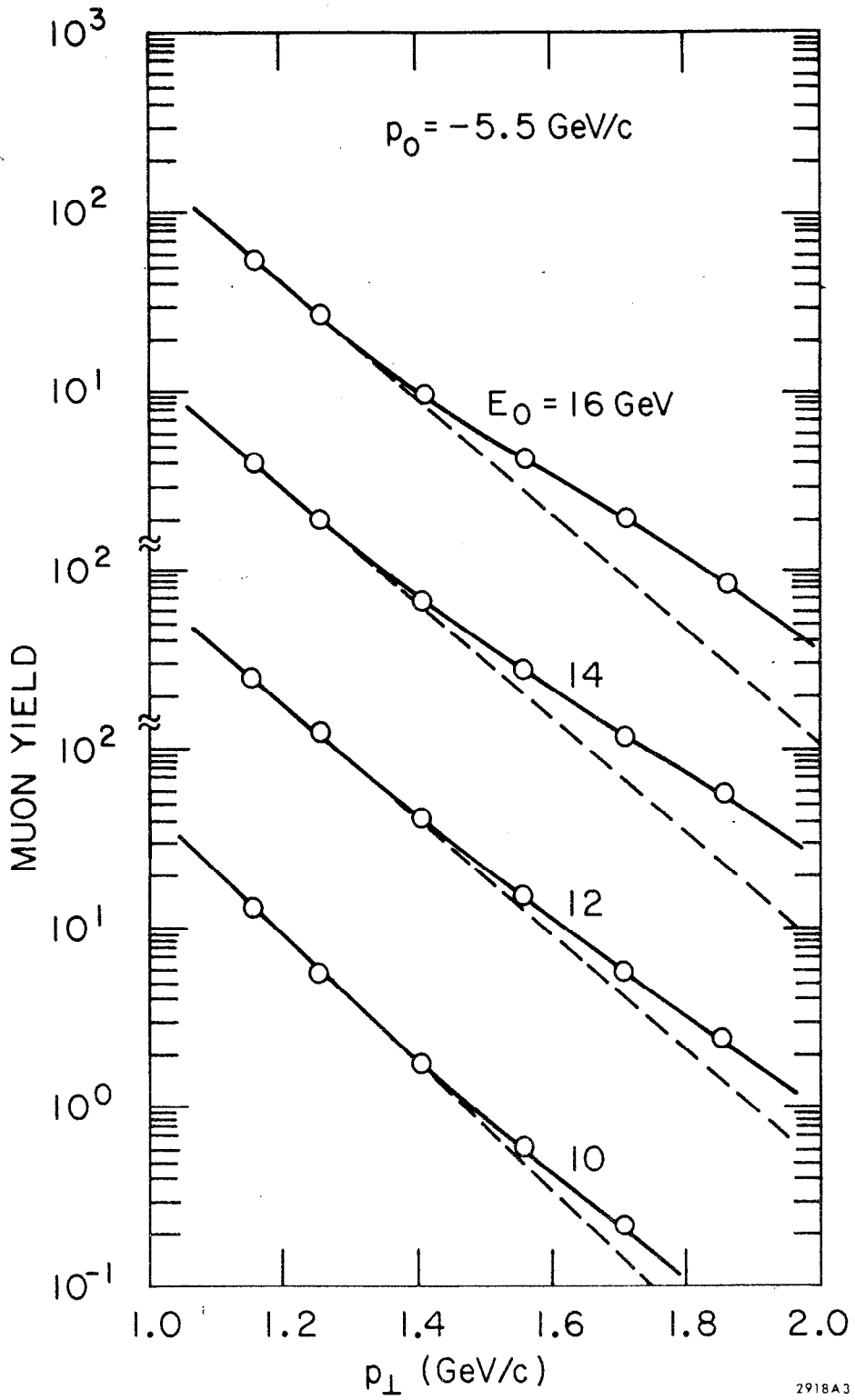

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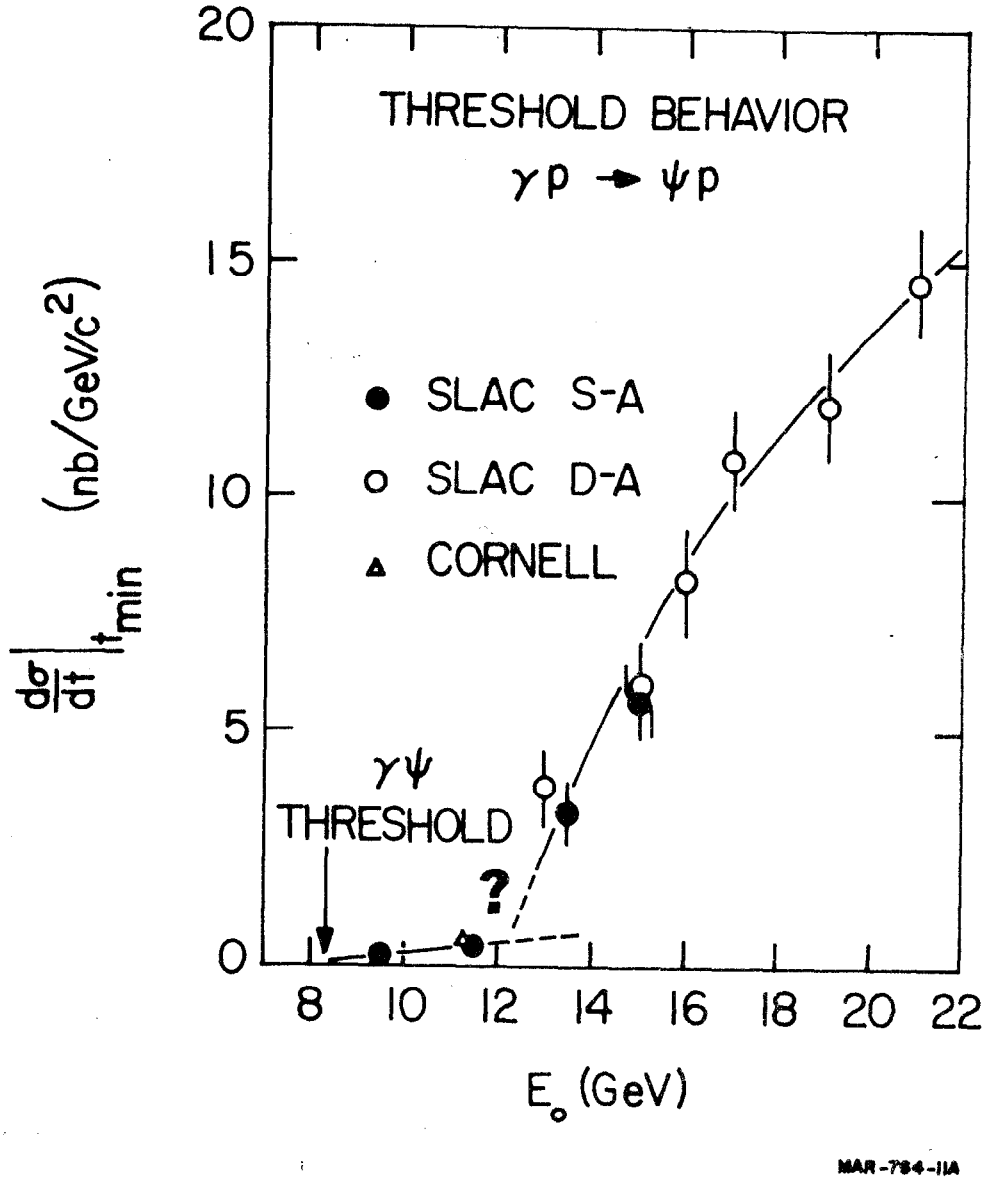

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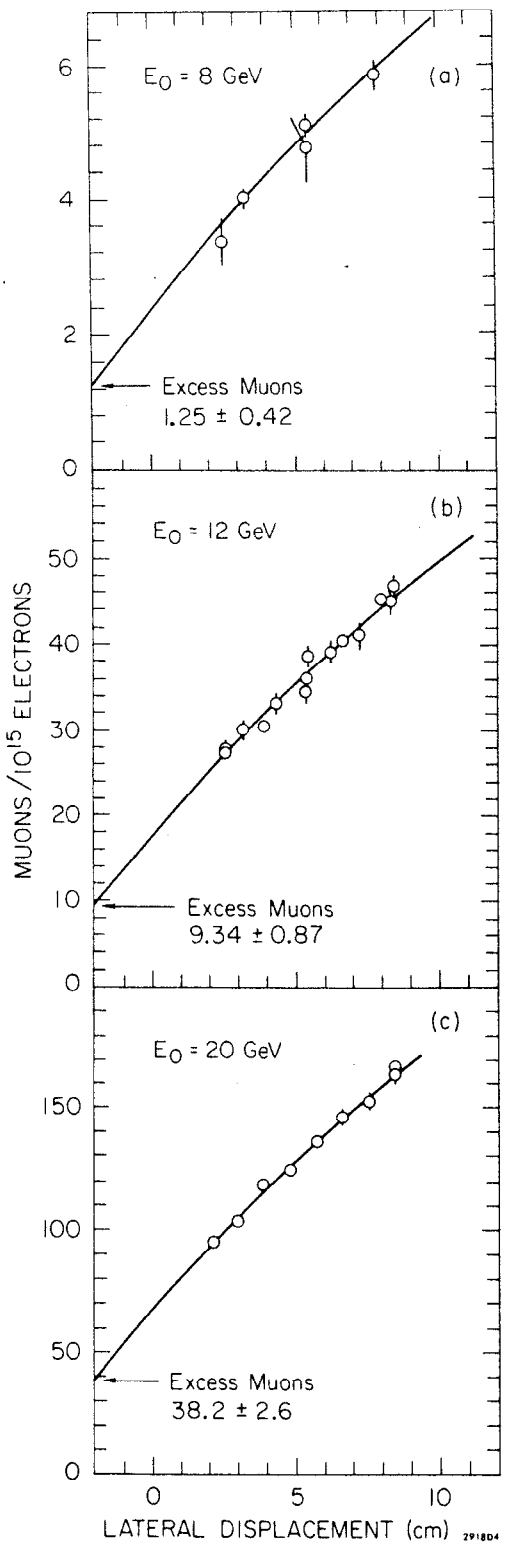

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