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OBSERVATION OF PROMPT SINGLE-MUON PRODUCTION BY 400 GEV PROTONS*

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ABSTRACT

We have observed a prompt single-muon signal in the region $.8<p_t<2.5$ GeV/c produced by the interactions of 400 GeV protons in steel. The prompt $1\mu^+$ rate is comparable in magnitude to the prompt 2μ rate in the same kinematic region. If interpreted as originating from the production and muon decay of charmed particles, the 1μ signal corresponds to a charm production cross-section in the range of 15 to 70 μb/nucleon, depending on production parameters.

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The hadronic production of charmed particles has recently received considerable experimental and theoretical attention. QCD calculations have predicted cross-sections in the range 1-30 μb in 400 GeV p-N interactions{1}, with gluon fusion probably giving the dominant contribution. Previous searches for charm production have produced widely varying results{2,3,4,5,6}, ranging from upper limits of ~1 μb/nucleon {2,3} at 400 GeV to a recently reported signal of > 150 μb at the ISR{5}. The prompt neutrino signal reported by the CERN beam dump experiments{6}, if interpreted as a charm signal, corresponds to a production cross-section of 25-50 μb/nucleon (assuming linear A dependence){7}

One of the cleanest signatures of charm production is a prompt single-muon signal, since the branching ratio of charm into μν + hadrons is large (~10%) and other sources of prompt single muons are negligible. Several experimental groups{2,8,9} have reported sizable prompt muon production, but only two{2,9} have attempted to separate 1-μ from 2-μ events (the latter are due primarily to electromagnetic rather than weak decays). The results of both of these groups were consistent with all the prompt muon signal originating from 2-μ events.

We report here the observation of a prompt $1\text{-}\mu^+$ signal in the moderately high p_t ($0.8<p_t^{\mu^+}<2.5$ GeV) and low x_F ($10<E^{\mu^+}<60$ GeV) region produced by 400 GeV p-N interactions. We observe approximately equal rates of $1\text{-}\mu^+$ and $\mu^+\mu^-$ final states in this kinematic region.

The experiment was performed in the Fermilab N5 beam with 400 GeV protons at typical intensities of 3-5 10^5/sec. The primary elements of the detector (Fig. 1) were a fine-grained target-calorimeter of variable density{10}, a muon identifier (MI), and a toroidal muon spectrometer{11}.

The incident protons interacted in the target-calorimeter, which contained 45 76 x 76 cm steel plates, each followed by a scintillation counter. The plates were mounted so as to allow the plate spacing to be uniformly expanded as described below. The first 20 plates, which absorbed most of the hadron shower, were 3.8 cm thick and the last 25 plates 5.1 cm thick. The total hadronic energy, interaction point, and shower profile were determined from pulse heights recorded for each of the counters.

The MI consisted of 10 114x122x10.2 cm steel plates, each followed by 4 counters 28x122 cm. The information from these counters was used to insure that the tracks observed in the spark chambers were due to in-time muons. In addition, the total MI pulse height had clearly resolved peaks for 1- and 2-muon events, which allowed us to confirm that no 2-muon events were being misidentified as 1-μ events due to reconstruction inefficiency. This system gave very good acceptance for detecting muons of > 3.6 GeV, thereby making it possible to distinguish 1-μ and 2-μ events with high efficiency.

Three 3.5-meter diameter toroidal magnets downstream of the MI formed the muon spectrometer, which focused positive muons with a 17 kg field. Each magnet was made of 8 20 cm thick steel washers with a 25 cm diameter hole through the center for the magnet windings. The total transverse momentum kick was 2.4 GeV/c{11}, giving a resolution $\Delta p/p$ of 10% due to multiple scattering. The toroid system was instrumented with counters and spark chambers as shown in figure 1.

The data reported here were taken with a high-p_t trigger, which required a coincidence of both a beam and a muon trigger component. The muon component required the muon to remain in the same quadrant throughout the toroid system by requiring the appropriate coincidence of counters

C, S2, ACR, T4 (which were divided into quadrants) and S1, T2, T3, MV (divided into half-planes). This requirement preferentially selected positive muons with high p_t ($p_t^{\mu^+} > .8$ GeV).

The beam component required an incident proton to pass through counters B0 and B1 (7.6x7.6 cm and 5.1x5.1 cm) and to interact within the first 10 plates of the calorimeter. To reject any background from upstream interactions, triggers were vetoed by the presence of any additional particles in the beam or halo counters within 95 nanoseconds of the trigger. Further beam information was provided by the pulse height of the trigger counters and by the incident proton's trajectory and momentum, as measured by a spectrometer immediately upstream of the calorimeter. Interactions satisfying the beam trigger alone were scaled, and one out of each 2^{16} was recorded to provide a control sample of interactions without any muon requirement.

In the data analysis, software cuts were made to insure that the muon trigger counters were associated with a good μ^+ trajectory, that the μ^+ enter the toroid system at least 17.5 cm from the axis (outside of the hole), and that the interaction point lie between plates 1 and 8 of the calorimeter. The muon trigger acceptance after all these cuts was greater than 50% over the range $1.0 < p_t^{\mu^+} < 2.5$ and $20 < E^{\mu^+} < 60$ GeV.

The majority of muons which triggered the apparatus were due to pion and kaon decays. This background was measured by uniformly expanding the first 25 plates (1 meter of steel) of the calorimeter, thereby proportionally increasing the mean path length and decay probability of hadrons in this region. Most of the hadrons decaying downstream of this region were produced by secondary or tertiary interactions, and consequently

gave decay muons that were generally too low in energy to satisfy the trigger.

The experiment collected data at three different densities: fully compacted, expanded by a factor of 1.5, and expanded by a factor of 2. The mean calorimeter density in the compacted configuration was 3/4 that of steel due to the gaps (1.3 cm) between plates. After all software cuts, the rates in each density configuration were normalized to the beam trigger rates and plotted as shown in figure 2. As expected, the 2-μ rate is flat, and the 1-μ rate shows a linear increase with the effective pion interaction length. The 1-μ slope measures the rate from non-prompt decays, and the intercept of $(10.5 \pm .5)10^{-6}$ at infinite density is the raw prompt 1-μ signal. The distribution of these extrapolated prompt 1-μ events as a function of measured transverse momentum p_t is shown in figure 3; the smooth curve is the acceptance of the apparatus estimated using the models described below.

To obtain the true prompt single muon rate, the raw prompt 1-μ rate had to be corrected for several background sources:

a) $\mu^+\mu^-$ events with a low energy μ- which ranged out in the calorimeter or muon identifier. A Monte-Carlo calculation using the measured $\mu^+\mu^-$ distributions gave a correction of 24±5% (systematic errors included) of the 2μ signal, and therefore 10±2% of the raw prompt 1μ signal. This component was subtracted from the 1-μ signal and added to the 2-μ signal.

b) Muons from decays of pions and kaons in the unexpanded part of the calorimeter (after plate 25). A Monte-Carlo simulation of the hadron shower, which reproduced the mean shower profile measured in the experiment, gave a correction of 8±3% of the measured decay rate{12}. This corresponds to 16±6% of the prompt 1-μ signal.

c) Changes in trigger efficiency due to expansion of the calorimeter. Although the mean beam interaction point was held at fixed position when the calorimeter was expanded, the mean production point of pions and kaons from secondary interactions and the mean multiple-scattering center of all muons were necessarily moved downstream. Since the toroid hole subtended a larger angle for particles originating farther downstream, this introduced a reduction in acceptance for the expanded configuration relative to the compacted configuration. From the measured change in the 2-μ rate, and from the linearity of the measured 1-μ rates, we estimate this change to be 4±2%. Due to the magnification introduced by the extrapolation, this necessitated a subtraction of 20±10% of the prompt 1-μ signal.

Each of these last two backgrounds had the effect of enhancing the signal from beam interaction in the downstream plates, since the showers from these penetrated farther downstream. Figure 4 shows the ratio of the number of raw prompt 1-μ events to the total number of beam interactions as a function of interaction plate. Fitting the shape of this distribution to a linear combination of the downstream decay distribution and a flat prompt distribution gives a relative background of 20±16%, consistent with the Monte-Carlo estimate of 16%.

After all corrections, the measured prompt 1-μ rate was $(5.8\pm1.5)\times10^{-6}$/ $\times10^{-6}$/incident proton and the 2-μ rate was $(5.9\pm.2)\times10^{-6}$; the errors are largely systematic.

To estimate a charm production cross-section from these data, we have assumed that all the signal comes from the semileptonic decays $D\to K\mu\nu$ and $D\to K^{*}\mu\nu$ with branching ratios of 6% and 4%, respectively. The inclusive D

cross-section was assumed to increase linearly with the atomic number A of the nucleus and was parameterized as

$$E\frac{d^3\sigma}{d\rho^3} = C\,(1-x_F)^{\beta}e^{-\alpha p_t}$$

The data were consistent with values in the range α = 2.0-3.5 GeV^{-1} and $\beta > 3$. For $\beta = 5$ and $\alpha = 2.5\ GeV^{-1}$, the acceptance for produced μ^+'s was 2.1% and the cross-section for D production was $\sigma_{D\bar{D}}$ = 36μb/nucleon. Varying α and β over the allowed ranges produced cross-sections in the range 15-70μb/nucleon. The data were also consistent with a model in which the D's were produced in pairs of mass M with $M^3\frac{d\sigma}{dM} = e^{-.55M}$ and with the composite $D\bar{D}$ system produced with $\alpha = 2.23\ GeV^{-1}$ and $\beta = 2.96$ (as measured for the ψ in this experiment {11}); this model gave a cross-section of 22μb.

The primary source of the large uncertainty in $\sigma_{D\bar{D}}$ is the uncertainty in the extrapolation to $p_t^{\mu^+} = 0$ and $p^{\mu^+} = 0$. This source of error does not apply to the partial prompt 1-μ rate in the region $p_t^{\mu^+} > 1.0$ GeV and $p^{\mu^+} >$ 20 GeV. Correcting for backgrounds, acceptance, and multiple-scattering feed-down from lower p_t, we estimate a rate of $(2.1 \pm 0.7)\times10^{-6}$/incident proton in this restricted kinematic range.

To summarize, we have observed a clear signal of prompt 1-μ events in the region $.8<p_t^{\mu^+}<2.5$ GeV and $12<E^{\mu^+}<60$ GeV produced by 400 GeV protons on steel, and have measured approximately equal rates of 1-μ and 2-μ events in this kinematic region. These prompt 1-μ events are consistent with a charm-decay source if the charm cross-section is within the range 15-70 μb/nucleon{13}, where the errors reflect model-dependent uncertainties rather than statistical error in the data.

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12. Recent measurements of downstream decays, using a similar trigger in a modified version (Fermilab E595) of this experiment, have confirmed this Monte-Carlo estimate.

13. Other measurements relating to charm production by hadrons are contained in the proceedings of "Cosmic Rays and Particle Physics 1978" (Bartol Conference), Newark, Delaware, 1978.

Figure Captions:

1. Calorimeter, muon identifier, and spectrometer system.
2. Measured $1\mu^+$ and 2μ rates as a function of calorimeter density (the statistical error at each point is smaller than the dot size). The points at infinite density ($\lambda_\pi = 0$) are the extrapolated prompt rates.
3. The measured p_t distribution of observed prompt $1\mu^+$ events (uncorrected for resolution or acceptance). The smooth curve is the estimated acceptance of the apparatus.
4. Uncorrected prompt $1\mu^+$ events/proton interactions as a function of shower vertex. The dashed line shows the shape expected from background decays in the unexpanded part of the calorimeter, and the solid line is the fit obtained with a background of 16% (best Monte-Carlo estimate).

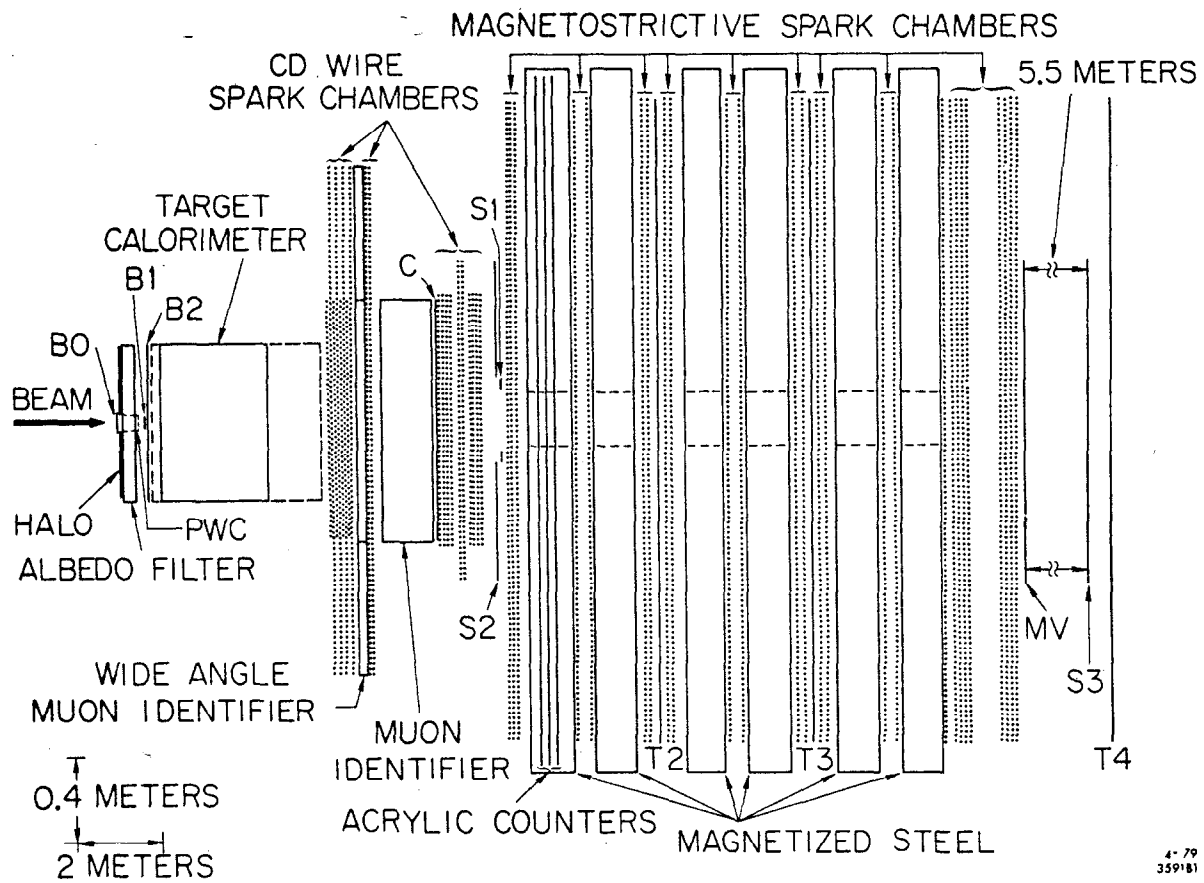
MAGNETOSTRICTIVE SPARK CHAMBERS
CD WIRE
SPARK CHAMBERS
5.5 METERS
TARGET
CALORIMETER
S1
C
B1
B2
B0
BEAM
HALO
PWC
ALBEDO FILTER
S2
MV
S3
WIDE ANGLE
MUON IDENTIFIER
MUON
IDENTIFIER
T2
T3
T4
0.4 METERS
2 METERS
ACRYLIC COUNTERS
MAGNETIZED STEEL
4-79
359181

FIG. 1

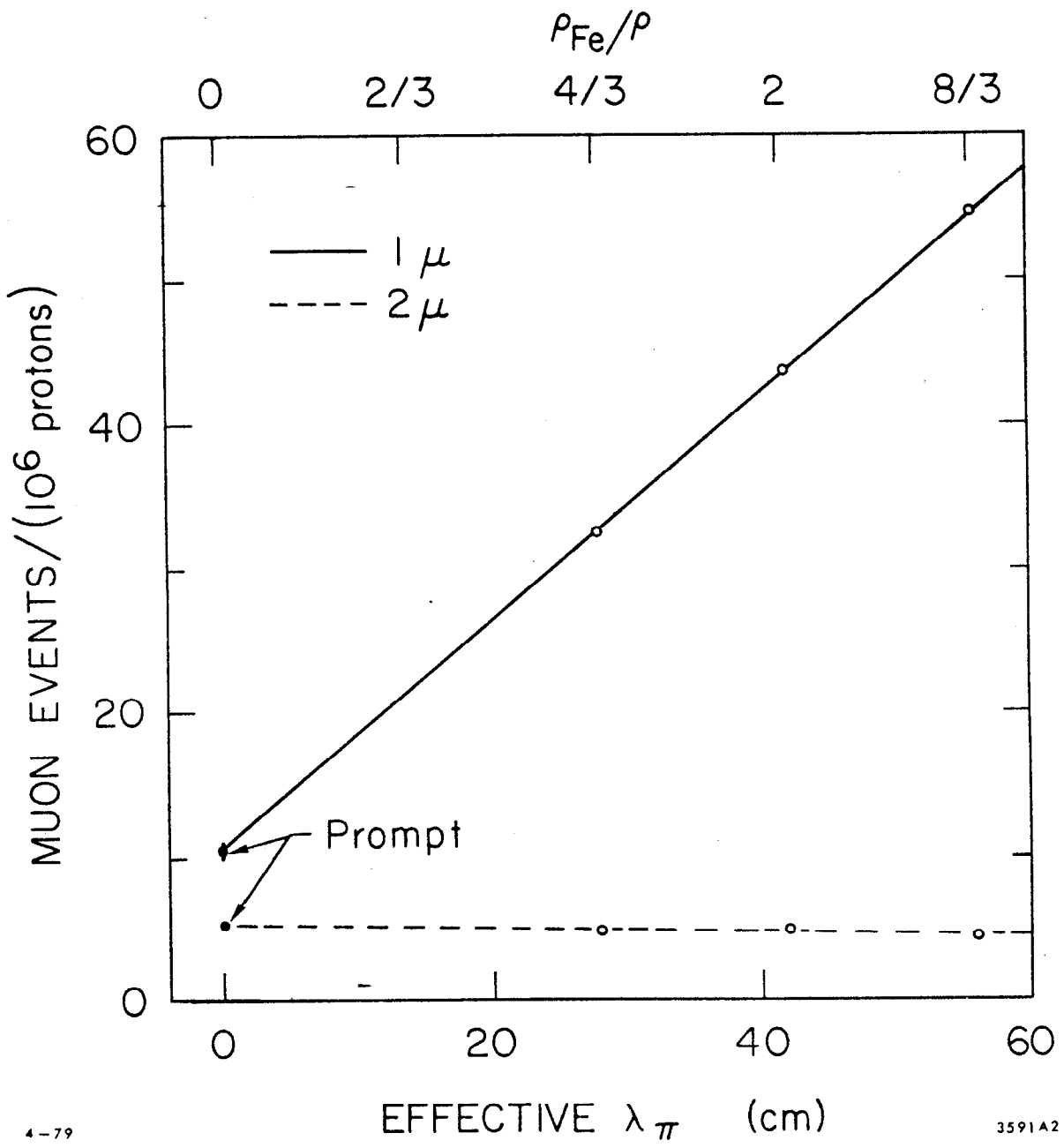
ρ_{Fe}/ρ
0
2/3
4/3
2
8/3
60
40
20
0
1 μ
2 μ
Prompt
MUON EVENTS/(10⁶ protons)
0
20
40
60
EFFECTIVE λ_π (cm)
4-79
3591A2

FIG. 2

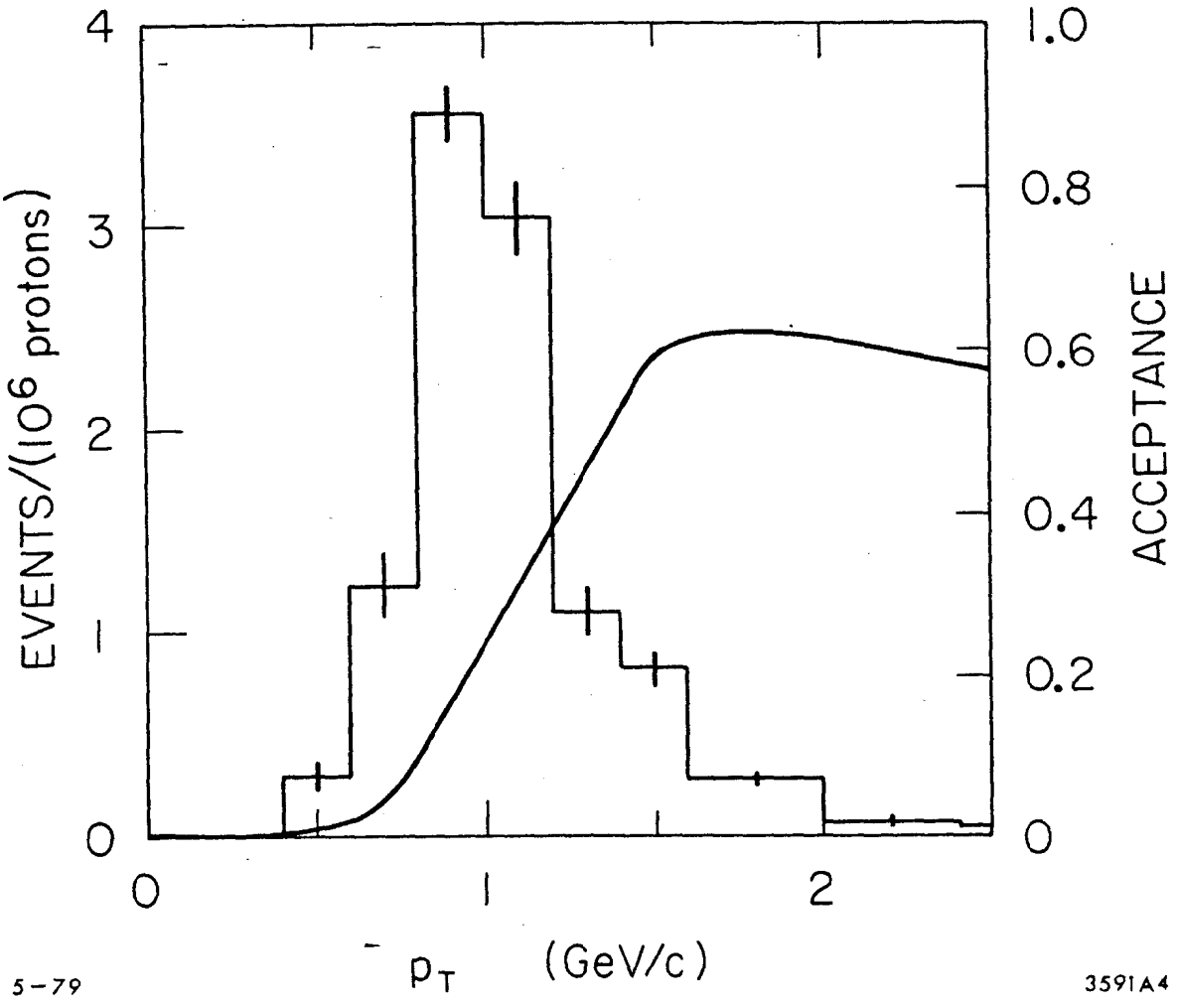
4
3
2
1
0
EVENTS/(10⁶ protons)
1.0
0.8
0.6
0.4
0.2
0
ACCEPTANCE
0
1
2
p_T (GeV/c)
5-79
3591A4

FIG. 3

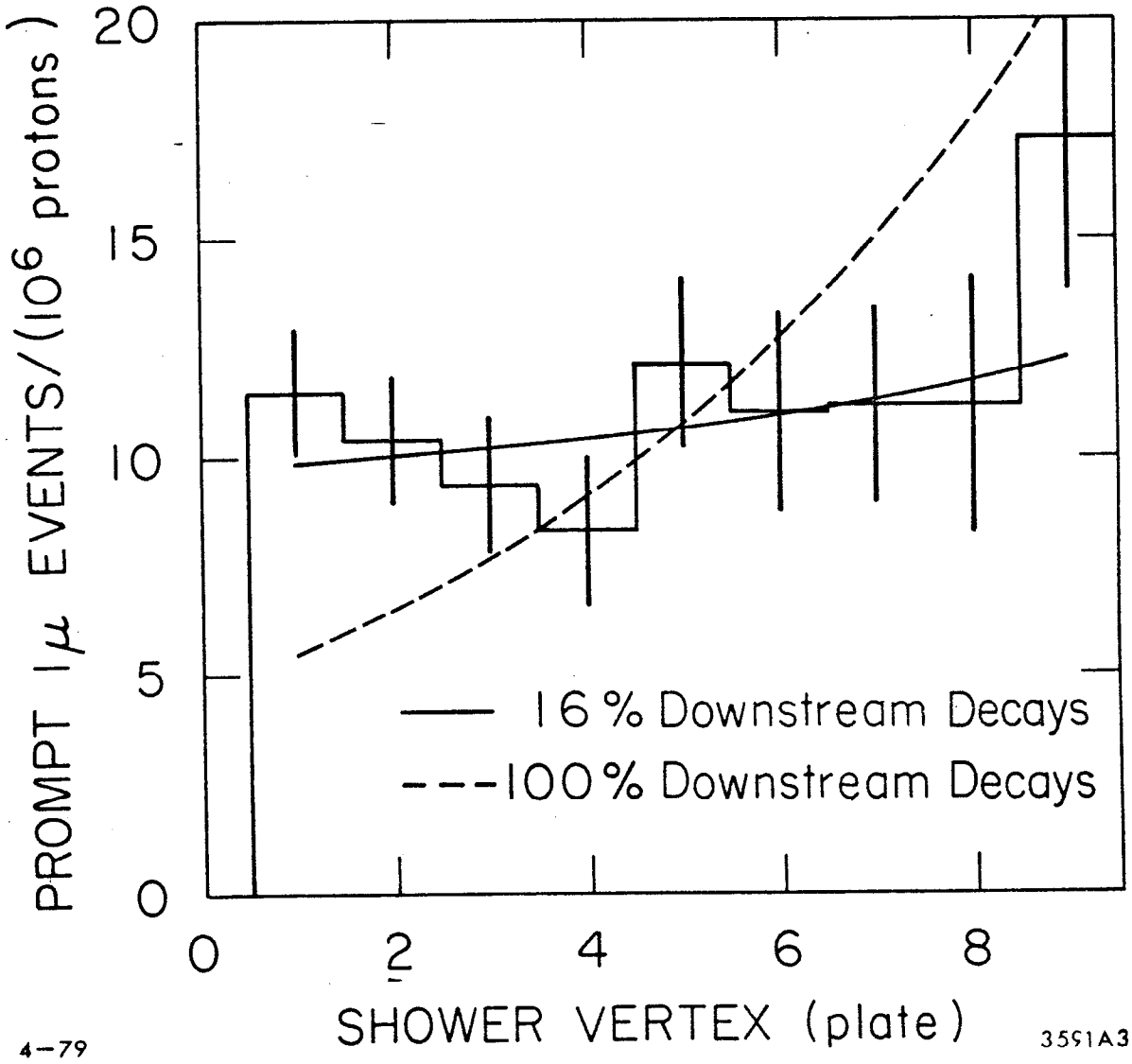
PROMPT 1μ EVENTS/(10⁶ protons)
20
15
10
5
0
0
2
4
6
8
SHOWER VERTEX (plate)
16 % Downstream Decays
100 % Downstream Decays
4-79
3591A3

FIG. 4