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OBSERVATION OF PROMPT SINGLE MUON PRODUCTION BY HADRONS AT FERMILAB*

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ABSTRACT

Talk given by M. H. Shaevitz at the Third International Conference at Vanderbilt University, March 3-6, 1978, on New Results in High Energy Physics. In an experiment at Fermilab, we have measured prompt single and dimuon production by 400 GeV protons in a large acceptance detector. A substantial prompt single muon rate has been observed in the region $.7 < p_\perp < 1.5$ GeV/c and $x_F < .25$ indicating the production and weak decay of heavy short-lived sources. If interpreted as charmed particle production, a model dependent calculation indicates a cross section for pp → charm + anything of approximately 40 μb.

INTRODUCTION

The discovery[1] in 1974 of large rates for prompt lepton production by hadrons started a great effort to determine the short lived sources. Recent experiments[2] have indicated that most prompt leptons are from lepton pair sources and are, therefore, electromagnetic in origin. A question immediately arises - are there also weakly decaying prompt sources? Experimentally, a weak decay is characterized by a single charged lepton and an undetected neutrino. We have performed an experiment at Fermilab to isolate these weak sources, by separating single muon from dimuon events and by measuring "missing energy" indicative of undetected neutrinos. This report is intended to be a brief statement of our progress; the results are very preliminary and are obtained from a very small part of the data sample (~15%).

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APPARATUS

Basically, the experiment consists of a target-calorimeter followed by a muon spectrometer (Fig. 1). A 400 GeV proton beam is incident on the target-calorimeter; the momentum and direction of the beam are measured by an upstream PWC spectrometer. Beam halo and off-momentum particles are eliminated by counters upstream of the calorimeter. Good beam particles are required by the trigger to interact in the first 15 inches of Fe in the calorimeter and to be unaccompanied by additional beam within 60 nanoseconds.

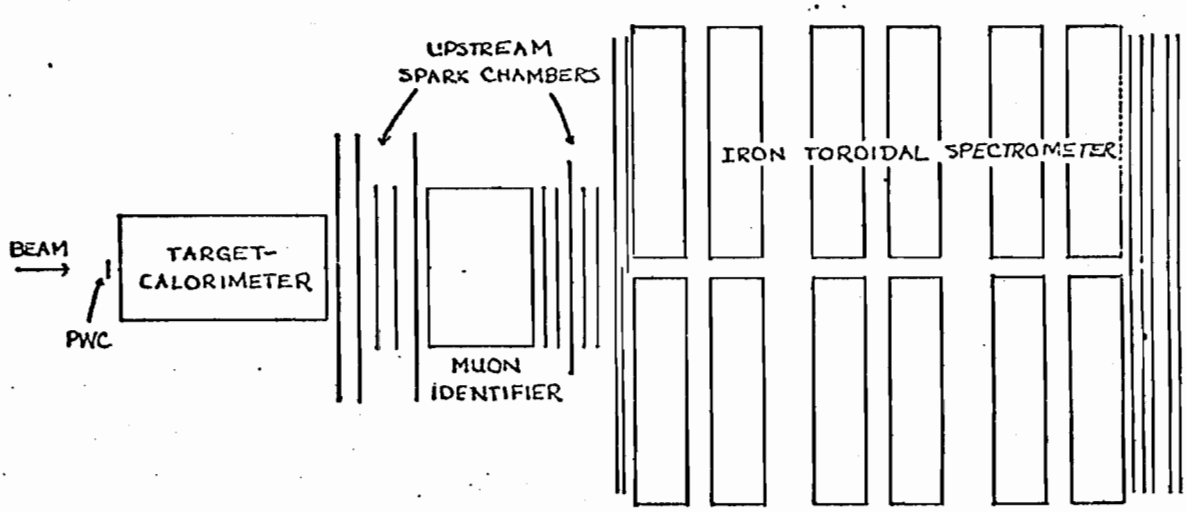

Fig. 1 - Plan view of the apparatus (not to scale).

The target-calorimeter consists of 1.5 and 2" Fe-scintillator sandwiches and measures the total energy in the hadron cascade. Phototube gains and rate effects are monitored by several devices allowing a measurement of total energy to ± 3.6% at 400 GeV. Downstream are spark chambers to measure the angle of muons exiting the calorimeter, a 1m muon identifier and a 40 foot long 12 foot diameter iron toroidal magnet system to measure muon momentum. The total $\int Bdz$ of the magnet system is 3200 Kg-in, corresponding to radial kick of 2.4 GeV/c and a momentum resolution of 9%.

DIMUON RESULTS

The experiment ran for 12 weeks and recorded about four million triggers with a total integrated flux of $\sim 10^{11}$ protons. The large acceptance of the apparatus makes it ideally suited for measuring the production distributions of high mass dimuon sources. The dimuon invariant mass distribution (uncorrected for acceptance) for 25% of the data is shown in Fig. 2; a clear ψ peak is in evidence with a width consistent with momentum resolution and multiple scattering in the calorimeter. Defining the ψ region as $M_{\mu\mu}$ between 2.4 and 4.0 GeV

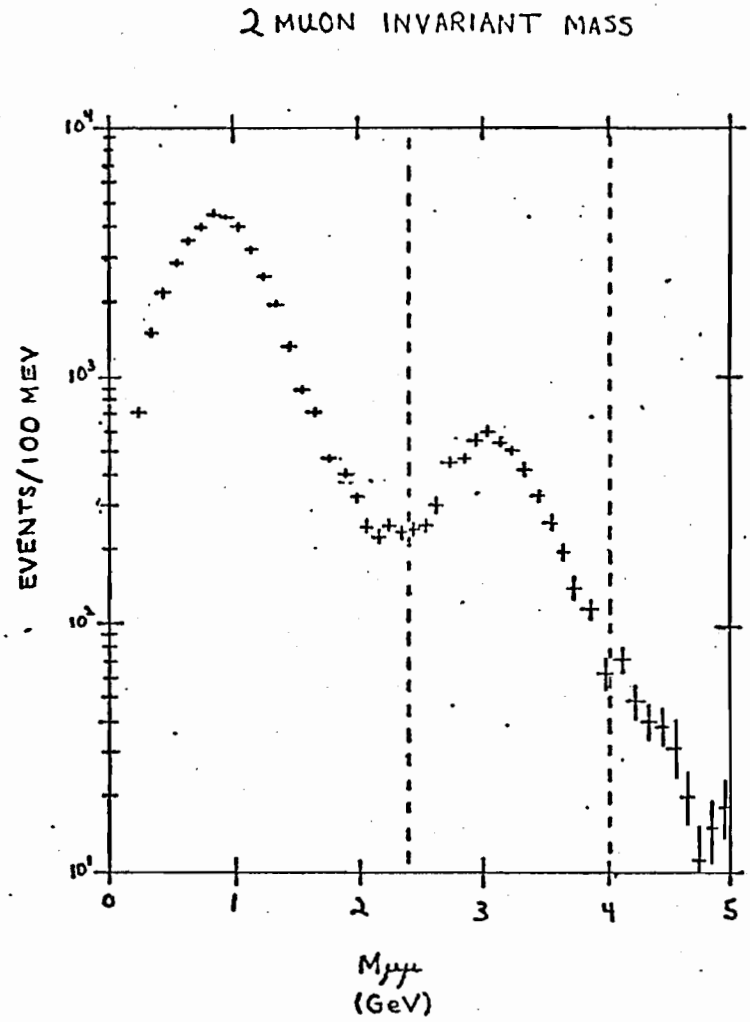

Fig. 2 - Dimuon invariant mass (uncorrected for acceptance). Approximately 5300 events in the ψ-region.

yields 5300 events covering the range $0 < p_\perp < 5$ GeV/c with good acceptance; Fig. 3 shows the $p_\perp$ distribution for these events corrected for trigger efficiency. (The efficiency was calculated via Monte Carlo assuming a flat decay angular distribution in the ψ rest frame and $p_\perp$ and x_F distributions consistent with those observed). The best fit to the form $dN/dp_\perp^2 \propto e^{-bp_\perp}$ for $p_\perp > 1.2$ gives $b = 2.04 \pm .05$ in good agreement with the $p_\perp > .4$ GeV data of Branson et al.[3] A similar fit gives $\frac{dN}{dx_F} \propto (1-x_F)^c$ with $c = 4.87 \pm .26$ for positive x_F. It should be noted that contributions from secondary interactions have been determined to be small in this region. Integrating the distributions (assuming a linear A dependence for production and assuming symmetric distributions around $x_F = 0$) yields a total cross section

$$B(\psi \to 2\mu) \cdot \sigma_{tot}\ (pN \to \psi + X) = 17.0 \pm 3.1 \text{ nb/nucleon.}$$

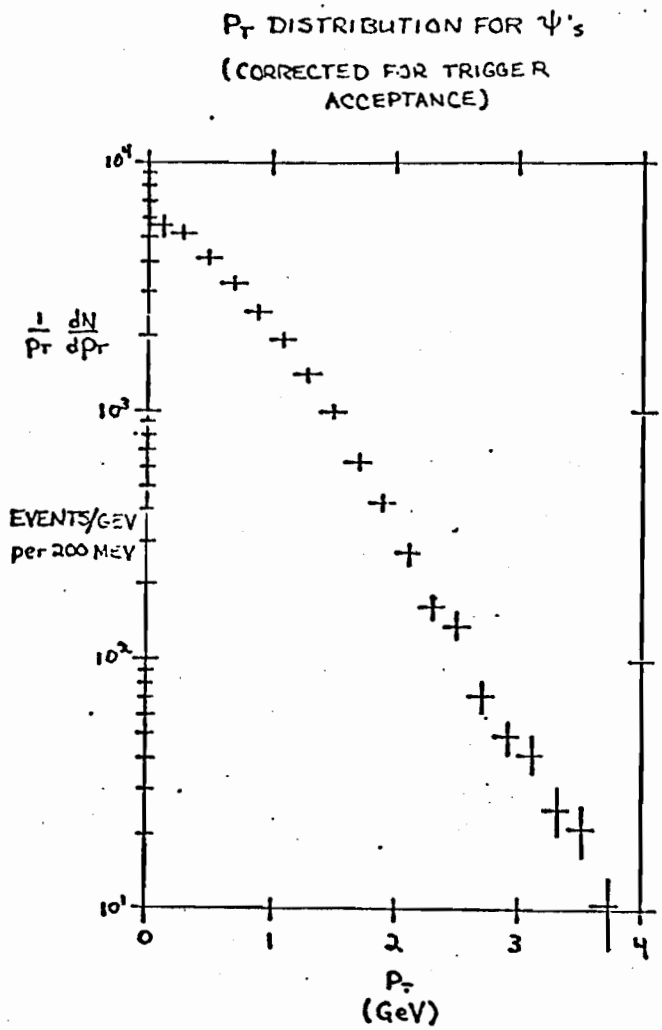

Fig. 3

$p_\perp$ distribution for events in the ψ region with $2.4 < M_{\mu\mu} < 4$ GeV, which have been corrected for acceptance but not resolution smearing. Best fit to the form $\frac{dN}{dp_\perp^2} \propto e^{-bp_\perp}$ yields $b = 2.04 \pm .05$ for the region with $p_\perp > 1.2$ GeV/c.

SINGLE MUON RESULTS

A primary motivation of this experiment is to search for prompt single muons. Events with one observed muon can come from three sources: (1) decays of long lived particles (non-prompt), e.g. pions, kaons, and hyperons; (2) two muon events in which only one muon is observed (di-muon feed-down), and (3) weak decays of short lived particles (prompt single muons). Non-prompt decay contamination is empirically removed by varying the density of the target-calorimeter while keeping the mean interaction point fixed to minimize any differences in geometric acceptance, and extrapolating the observed rate to infinite density. In Fig. 4(a), an example of this extrapolation is shown for a region dominated by non-prompt decay ($p_\perp < .2$ GeV/c); the data points are linear and consistent with no signal at the intercept.

Dimuon feed-down into single muon events is primarily eliminated by detecting both muons in the apparatus. Geometrically, the muon identifier and upstream spark chambers cover greater than 90% of 4π steradians in the center of mass; muons are detected with momentum as low as 3.5 GeV/c in the lab frame.

The small number of events in which one muon from a pair is unobserved has been calculated using a Monte Carlo program that generates events according to previously measured dimuon distributions;[4] these events typically come from moderate mass pairs ($\overline{M}_{\mu\mu} \sim$ 700 MeV) where one muon ranges out in the calorimeter. This correction is always small (less than 12% of the single muons and averaging 6%) because second muons are detected down to 3.5 GeV/c. (We plan, in the future, to use our measured two muon distributions to do this correction empirically.)

Fig. 4 - Density extrapolation plots. Prompt muons appear as a signal at 1/density = 0; the slope of each plot is proportional to the rate from muons from non-prompt decay. (Rates are those observed and have not been corrected for geometrical acceptance). The 1μ signal has been corrected for 2μ feed-down (typically 4-10%).

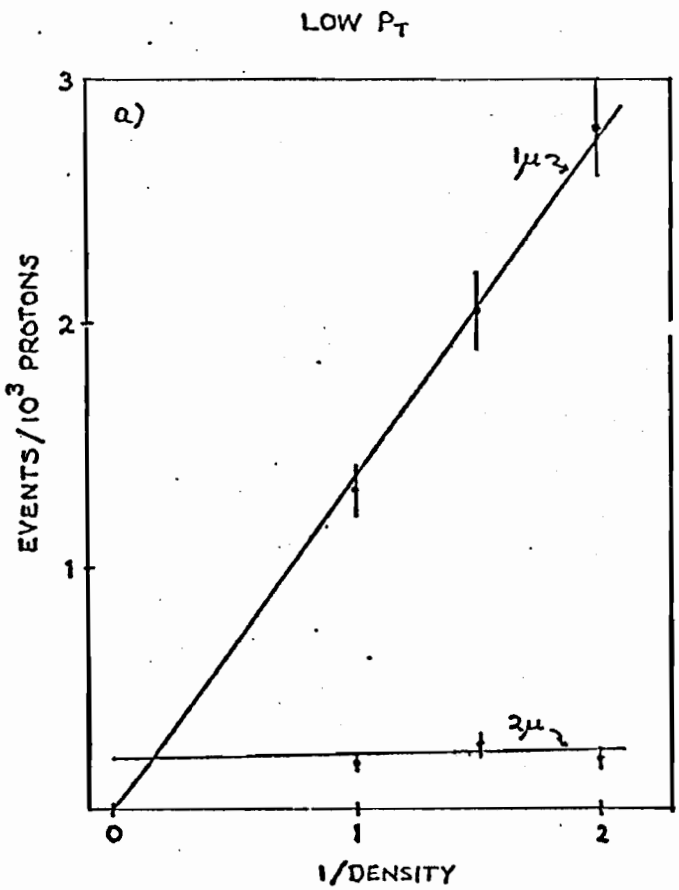

Fig. 4(a)

Very low $p_\perp$ region - dominated by non-prompt decay.

A combination of triggering configurations allowed the measurement of single muon production in two regions: (1) $x_F \sim 0$ and $p_\perp \geq .5$ GeV/c and (2) $x_F \geq .05$ and $p_\perp \geq 0$. The single and dimuon rates for these regions are shown in Fig. 4(b) and (c) versus inverse density; the extrapolations are linear with significant positive intercepts for the single muons.

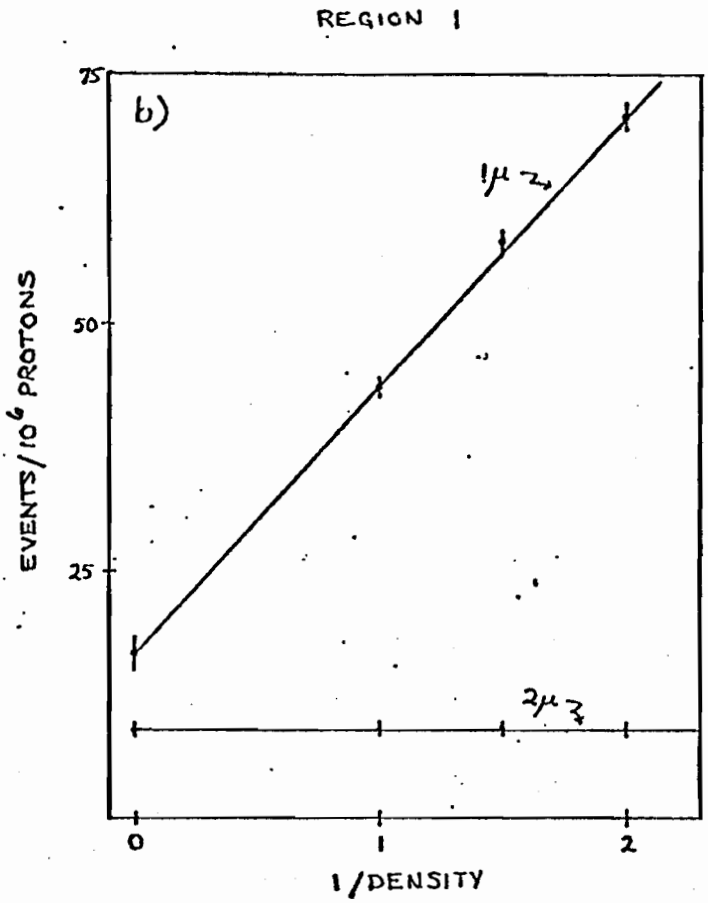

Fig.4(b)

Region (1) -
$p_\perp > .5$ GeV/c and
$x_F \sim 0$.

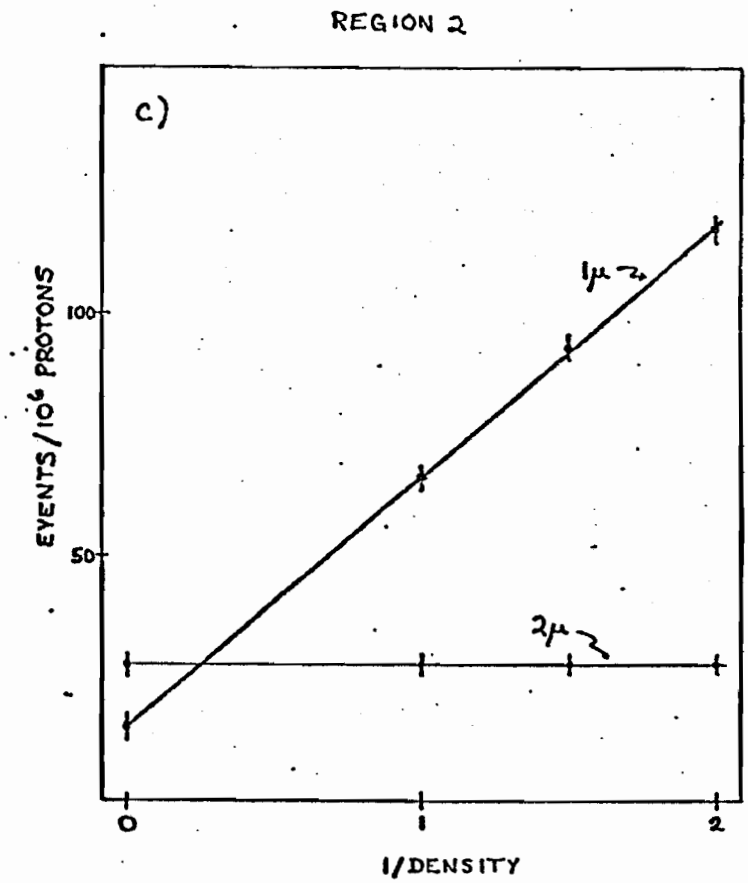

Fig. 4(c)

Region (2) -
All $p_\perp$ and $x_F > .05$.

Further evidence that single muons are produced is available by comparing the energy of the beam to the visible energy (E_{vis}); the energy sum of the hadron cascade and all muons. A difference between E_{beam} and E_{vis} could indicate missing energy carried off by neutrinos from a weakly decaying parent. An event by event comparison of E_{vis} and E_{beam} is precluded by the energy resolution of the calorimeter. However, a shift in the mean of the E_{vis} distribution for single muon events relative to muonless events can be measured. (The error in the mean is $14\ \mathrm{GeV}/\sqrt{N_{events}}$.) The missing energy, defined as the shift in the mean, at each density has contributions from non-prompt decay and prompt single muon sources. To separate the two contributions, the missing energy is plotted (Fig. 5) versus the fraction, α, of the single muons that are prompt for each density, (ρ).

$$\alpha(\rho) = \frac{\text{Prompt } 1\mu \text{ Rate}}{\text{Total } 1\mu \text{ Rate}}$$

The missing energy associated with the signal is then found by extrapolating to $\alpha = 1$. Using this procedure, the missing energy for the prompt signal in region (1), ($p_\perp \geq .5$ GeV/c) is 8.0 ± 4.2 GeV, consistent with the energy expected for an undetected ν from a heavy particle decay.

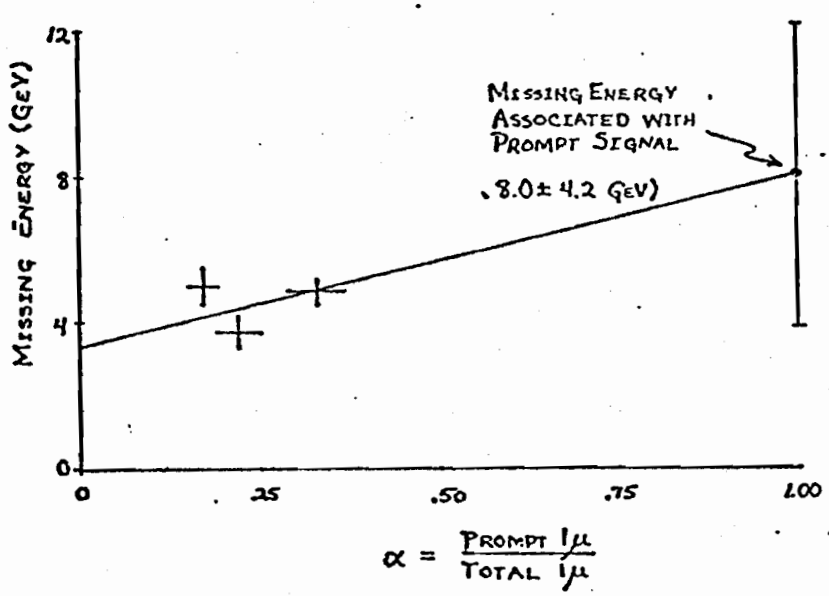

Fig. 5 – Missing energy signal vs. fraction of prompt 1μ for region (1) ($p_\perp > .5$ GeV/c). The missing energy associated with the prompt signla is found by extrapolating to $\alpha = 1$. A best fit to the three data points gives 8.0 ± 4.2 GeV for the prompt signal. A Monte-Carlo calculation using $(1-|x_F|)^{10}e^{-4p_\perp}$ for the pion production spectrum predicts ~ 4 GeV missing energy from π-decay, qualitatively consistent with the intercept at $\alpha = 0$.

In order to compare with previous experiments, we have calculated from the density extrapolation plots the μ/π ratio for the sum of single and dimuons as a function of x_F (Fig. 6). The ratio is about 10^{-4} at low x_F and falls to 10^{-5} for x_F above .3, in good agreement with previous measurements[2,6] at low $p_\perp$.

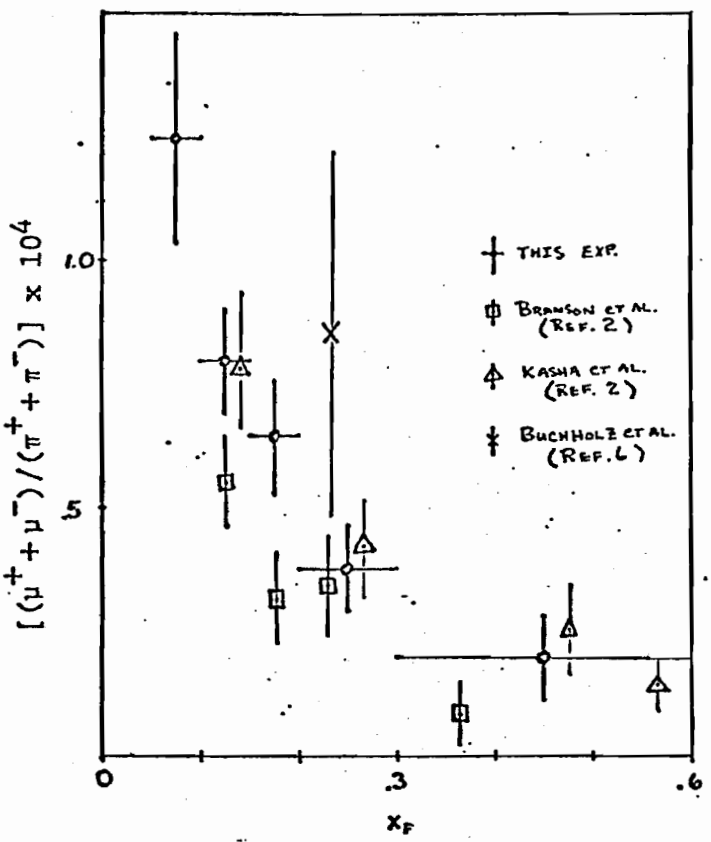

Fig. 6

The μ/π ratio vs. x_F for region (2) ($x_F > .05$). The different x_F points are obtained from the density extrapolation for data in each x_F bin. Basically, the ratio is found by dividing the total prompt signal (1μ and 2μ) by the slope of the extrapolation curves multiplied by the probability for a pion to decay. The results of Ref. 2 and 6 are also shown.

In figures 7 and 8, the ratio of single prompt muons to total prompt is presented as a function of x_F and $p_\perp$. The data show that the rate of single muons is small in regions explored by previous experiments at large $p_\perp$ and $P_{/\!/}$. However, in the region of $x_F < .25$ or $p_\perp < 1.5$ GeV/c, the prompt single muon signal is sizeable and accounts for about 50% of the total prompt rate; i.e., half of the prompt muons in this region do not come from muon pairs.

One possible interpretation for these results is that the single muons are predominantly from charm production. The $p_\perp$ and x_F distributions are qualitatively consistent with those expected from D(1865) production and subsequent three body decay ($D \to K\mu\nu$).[5] Assuming that the parent D meson is produced with the same distributions as we have measured for ψ's ($d^2N/dx_F dp_\perp^2 \propto e^{-2p_\perp} (1-|x_F|)^5$ the observed prompt single muon signal corresponds to a charm cross section

$$\sigma \text{ (charm)} \sim 40 \ \mu b$$

assuming $BR(D \to \mu + ..) = .11$ and a linear A dependence for production. It should be noted that the above cross section is very dependent on these assumptions. For example, with an assumed steeper dependence $(dN/dx_F dp_\perp^2 = e^{-3p_\perp}(1-|x_F|)^8)$ the cross section is a factor of 2.5 higher; for a flatter distribution the cross section would be correspondingly smaller. Also, for an $A^{2/3}$ dependence (assumed by the CERN beam dump experiments) our result would be larger by a factor of 2.5; including $D \to K^* \mu\nu$ would increase the cross section, etc. With the above caveats, we conclude that the prompt single muon signal, if interpreted as charm, indicates a cross section of approximately 20-80 μb.

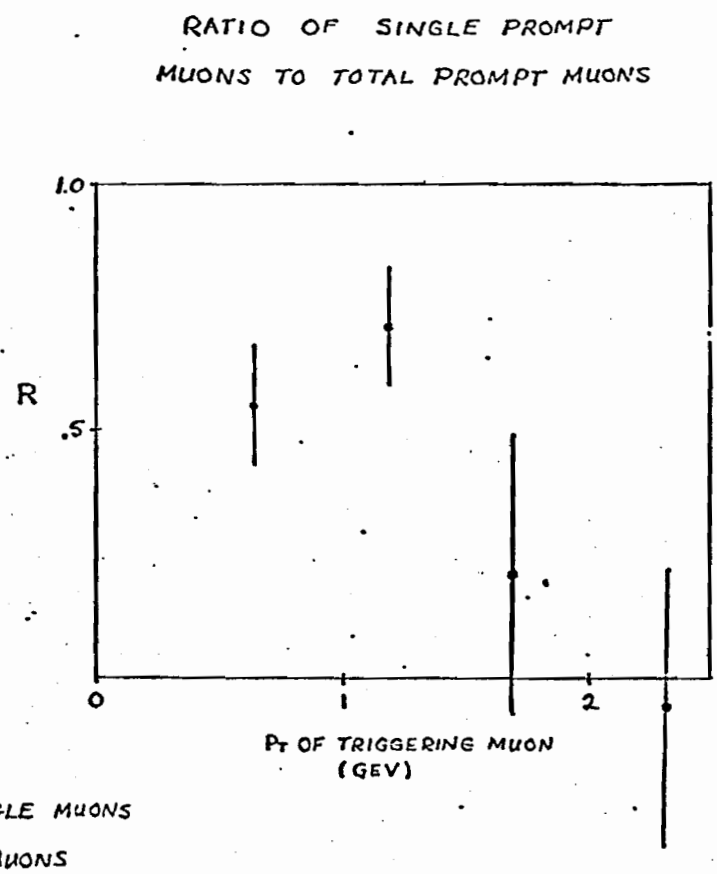

Fig. 7

Fraction of the total μ^+ prompt signal attributed to single muons vs. $p_\perp$ in region (1) ($p_\perp > .5$ GeV/c).

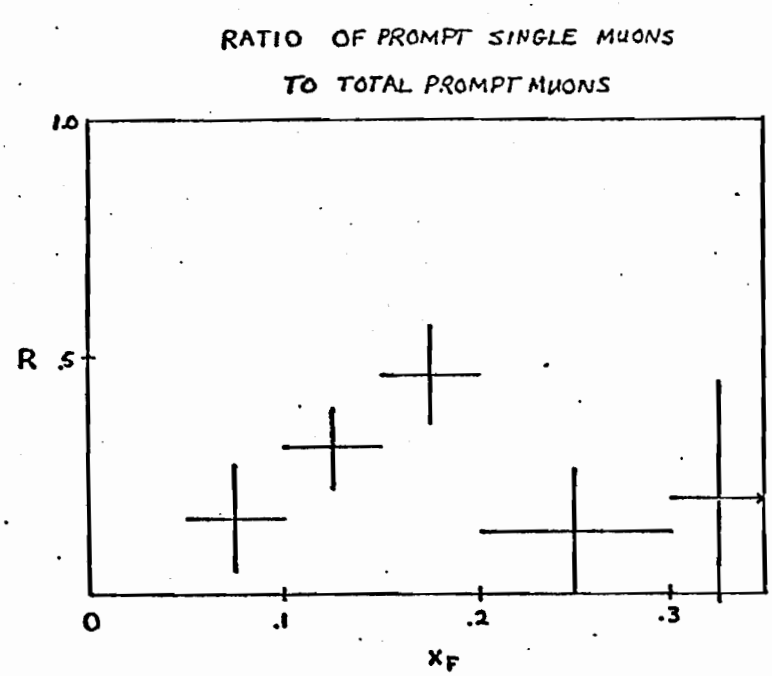

Fig. 8

Fraction of the total observed prompt signal attributed to single muons vs. x_F in region (2) ($x_F > .05$). A correction for difference in trigger efficiencies between 1μ and 2μ, which will raise the small x_F points, has not been applied to the data.

CONCLUSIONS

We have presented evidence for a significant source of single prompt muons in high energy hadron-hadron collisions. The single muon signal accounts for about half of the prompt muons in the low x_F region with $p_\perp \approx 1$ GeV/c and is associated with undetected energy (presumably associated with final state ν's); this behavior is consistent with production and weak decay of heavy short-lived particles, possibly charmed particles. As stated previously, the results are very preliminary and represent only a small fraction of the total data sample. In the near future, we plan to improve the statistics by a factor of five allowing a much better determination of the single muon signal at large $p_\perp$ and x_F.

Future experimentation will be needed to obtain the detailed dependence on $\sqrt{s}$, $p_\perp$, x_F, and incident particle type. We hope to carry out a program of such measurements in the future to help understand the sources and production mechanisms for the prompt single muons reported here.

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