RECENT DATA ON PROMPT SINGLE LEPTON PRODUCTION IN HADRON-NUCLEUS COLLISIONS

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SUMMARY

This report is a pre-view rather than a re-view of what will be the results of the recent (1979) CERN beam dump experiments, on prompt single muon production at small p_t and x_F in a FERMILAB beam dump type experiment by the Caltech-FNAL-Rochester-Stanford collaboration and on prompt single electron production in a π^- exposure of the tracksensitive target in BEBC at CERN. The essential details of the experiments are briefly described. There are possible hints in the CERN beam dump data that D mesons are not the only source for the prompt leptons.

I. Introduction

Prompt neutrino fluxes discovered about one and half years ago were interpreted as first evidence for charmed particle production in proton-nucleus collisions. The evidence came from electron events observed in the CERN neutrino detectors [1-4] when performing proton beam dump experiments. In such experiments the protons and their secondaries are absorbed as quickly as possible in a dense block of heavy material in order to minimize the flux of neutrinos from conventional sources (π, K, Λ, Σ). This residual neutrino flux was not sufficient to explain the rate of observed electron events which otherwise behaved like normal neutrino events (distributions in space, energy, and multiplicity). Therefore, they had to be attributed to a new source short-lived enough not to be absorbed prior to decay and the simplest was to assume charmed particles.[5]
Leptons from the weak decay of such short-lived parents ($\tau < 10^{-11}$s) are called prompt single leptons, in contrast to prompt muon (or electron) pairs due to e.g. electromagnetic vector meson decay, internal bremsstrahlung etc.

Further evidence for charmed particle production in proton-nucleus collisions came from prompt single muons observed in the (modified) narrow band beam neutrino detector at Fermilab. In this experiment[6] 400 GeV protons were shot into the target calorimeter part of the detector itself, and the prompt single muons were separated from the π and K decay muons by measuring their rates at three densities of the target calorimeter and extrapolating to infinite density.

If interpreted in terms of neutrinos and muons from semileptonic decay of D mesons (10% branching ratio) the observed prompt lepton fluxes lead to total cross sections for the production of D mesons by protons ranging from about 40 μb to several 100 μb with large statistical[1,2], systematic[3] or model assumption[6] uncertainties. Ignorance about the dependence of the cross section on the mass number A introduces an additional uncertainty of a factor of about $A^{1/3}$.

Since then charmed particle production has been observed more directly in proton proton collisions at the ISR: D-mesons were detected via $K\pi\pi$[7] and leptonic decay modes[8], Λ_c production was observed in the $pK\pi$ decay channel[9]. Also in these experiments the total production cross sections are rather uncertain, mainly due to uncertainties in branching ratios and production models[10].

During the past eight months more data have been collected on prompt single lepton production in hadron-nucleus collisions: at CERN the beam dump experiments have been re-done but with copper dump targets of different densities. At Fermilab a test experiment was done to study prompt single muon production at small x_F and small p_t in a still more modified narrow band beam neutrino detector. In a π^- exposure of the hydrogen filled tracksensitive target (TST) inside the N_e/H_2 filled BEBC events with single electrons have been observed.

It is mainly these last developments which will be reviewed - or rather pre-viewed (most of the results are still preliminary) - in this paper, followed by a discussion of a few points which cast some doubt on the D-meson origin as the only interpretation.

2. The CERN 1979 Beam Dump Experiments: Prompt Neutrinos

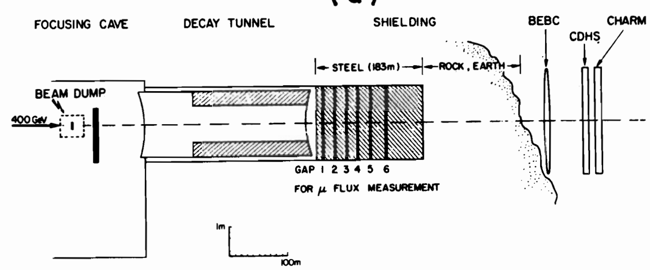
The main aims of the 1979 beam dump experiments were:
- to improve the statistics to check the equality of the prompt ν_e, $\bar{\nu}_e$, ν_μ, and $\bar{\nu}_\mu$ fluxes
- to use targets of different densities to establish better the non-prompt neutrino background and to allow a direct measurement of the prompt neutrino signal in the neutrino detectors by extrapolation to infinite density
- to disprove experimentally that proton beam scraping upstream of the dump target created the excess (prompt) neutrino events
- to reduce the above mentioned large range of D production cross sections
- and - as before - to search for other possible origins of prompt neutrinos

2.1 Layout and Experimental Details

Layout. A schematic plan of the beam and detectors is shown in figure 1(a). Protons of momentum 400 GeV/c are extracted during one revolution (23 μs) from the CERN SPS and focused onto the copper dump target. The construction of the dump targets used is shown in figure 1(b).

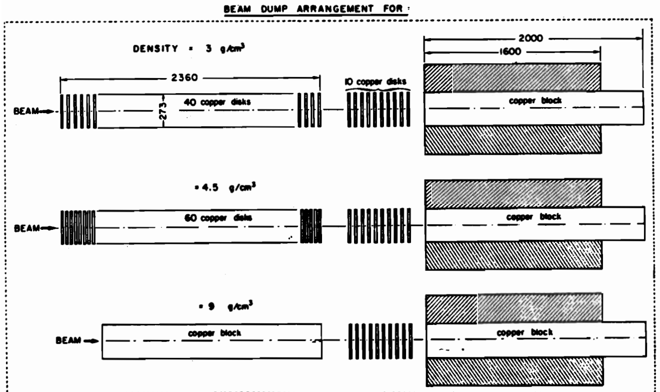
Figure 1a) Layout of the CERN 1979 Beam Dump Experiments.
1b) Details of Dump Construction.

(a)



(b)

BEAM DUMP ARRANGEMENT FOR



In addition to the solid copper target of density 9 g/cm^3, which will be referred to as full-density, targets of density 3.0 gm/cm^3 and 4.5 g/cm^3, which will be referred to as 1/3-density and 1/2-density respectively, were used. The effective dump densities of 4.5 and 3 g/cm^3 were achieved by arranging copper disks of 27 cm diameter and of 2 cm thickness spaced by 2 cm and 4 cm respectively, over a total length of 2.6 m, which is sufficient to absorb >99% of the primary protons. The dumps were water cooled. 72% of the experiments were made with the full-density dump, 28% with the 1/3-density dump. A short run, without neutrino detectors, was also performed, using the half-density target to measure the muon flux in the shielding.

Scraping monitoring. In order to ensure that neutrino fluxes come mainly from interactions and decays within the dump and not from proton interactions with the vacuum chamber wall upstream of the dump, the signals of eight radiation monitors (ionization chambers) installed along the ejected proton beam line were continuously recorded. These scraping monitors were calibrated such that a proton beam-loss of 1.7 x 10^{-4} (created by flipping 70μ thick aluminum foils into the beam) induced ∿2V signal in the monitors at 10^{13} protons per pulse. It is estimated that such proton interactions would increase the conventional dump flux by 15 to 30%. During normal running these scraping monitors were found to give signals less than 50 mV, thus keeping scraping contributions negligible.

Determination of the conventional neutrino flux. During the entire beam dump experiments the flux of muons in various gaps in the steel shield (Figure 1(a)) was measured using a system of solid state detectors, the charge signals of which were recorded pulse-by-pulse by a computerized data acquisition system[11]. These detectors have been cross-calibrated by using a moveable detector and also calibrated absolutely (to ±6%) by counting muon tracks in emulsions exposed in front of the detectors.

The muon flux consists of two components, those coming from the conventional flux (the decay of π and K mesons etc.) and those from prompt decay. The prompt decay component contains both electromagnetic (ρ, ω, ϕ, ψ etc.) and weak (charm etc.) decays. If targets of different density are used the prompt flux will remain the same but the conventional flux will be suppressed in the denser targets. The muon data have been analyzed from all three targets and in all cases no radial dependence (perpendicular to the beam axis) of the flux was observed in any of the gaps. Figure 2 shows a plot of the muon fluxes obtained with different density targets in the first 4 gaps, which correspond to minimum muon momenta of 23, 57, 94 and 136 GeV/c respectively. The quantity plotted is the flux averaged over a circle of 40 cm radius around the beam axis and corrected (to the case of full density) for the effect that muons in different targets traverse different amounts of material and hence undergo different amounts of multiple scattering and energy loss. The intercepts, at $1/\rho = 0$ obtained from straight line fits to the data of Figure 2, give the prompt muon ($\mu^-_{pr} + \mu^+_{pr}$) fluxes for different muon momenta. This prompt flux can then be subtracted from the measured muon flux to give the conventional decay muon flux, which via a model for particle production in proton-copper collisions (of π, K, Λ, Σ etc.) leads to an estimate of the conventional neutrino flux. This is shown in Figure 3. More details of this procedure, together with a discussion of the errors, including those introduced by the model, are given in Reference (12). The estimated overall error on predicted event rates from conventional neutrinos is ±11%. The sum of predicted μ^+ and μ^- events has a smaller uncertainty (8-9%).

Figure 2) Muon fluxes measured in the CERN Beam Dump Experiments as a function of $1/\rho$.

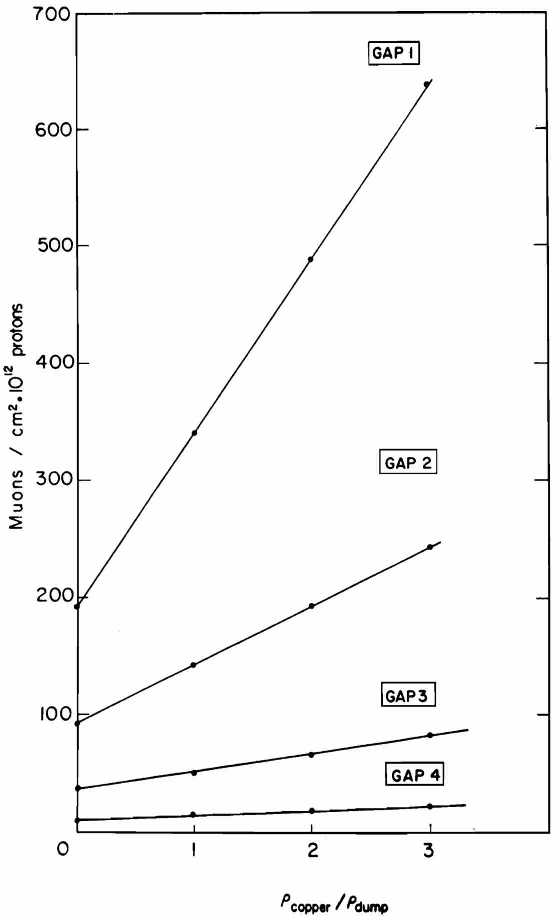
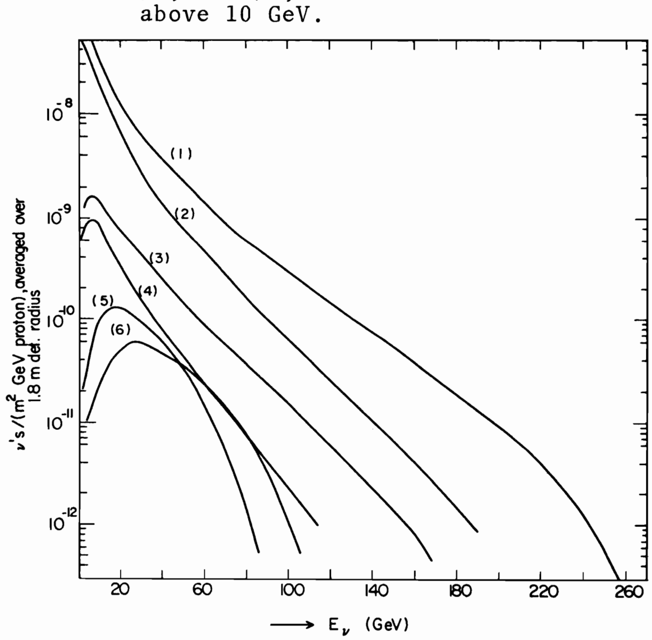


Figure 3) Conventional Neutrino Spectra: ν_μ (Λ) from $(\pi, K)^+_{\mu 2}$, $\bar{\nu}_\mu$ (2) from $(\pi, K)^-_{\mu 2}$, ν_e (3) from $(K^\circ, K^+)_{e3}$, $\bar{\nu}_e$ from $(\bar{K}^\circ, K^-)_{e3}$ (4), Λ_{e3} (5), and Σ^-_{e3} (6). The expected conventional background rate per ton and 10^{18} protons at the position of BEBC is 4.5 μ^-, 0.9 μ^+, 0.27 e^- and 0.08 e^+ events above 10 GeV.



The neutrino detectors. BEBC (820 m distant from the dump) was filled with a neon-hydrogen mixture of density 0.66 g/cm^3 (0.71 in 1977), has a fiducial volume of 19.3 m^3 and a magnetic field of 35 kG. A 2-plane External Muon Identifier (EMI) detects muons above 5 GeV with 98% efficiency. μ^--event rates are corrected for this cut assuming a flat y-distribution for μ^- events.

The CDHS detector[13] (890 m distant from the dump) consists of 5 cm (first 3/4 of the apparatus) and 15 cm thick magnetized steel plates (total length 20 m) with scintillator hodoscopes after every steel plate and wire chambers after every ∿ 40 cm of steel. The fiducial volume corresponds to ∿ 500 t.

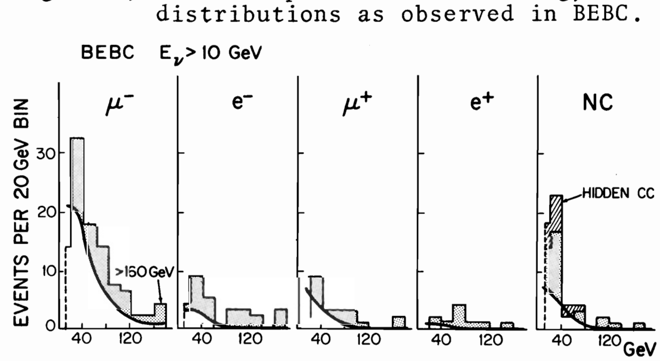
The CHARM detector[14] (910 m distance from the dump) consists of a segmented marble plate/scintillator calorimeter surrounded by a magnetized iron frame and followed by a toroidal muon spectrometer. The calorimeter is made of 78 modules each consisting of a marble plate (8 cm thick), a proportional drift tube plane (128 x 3 x 3cm^2 x 4m) and a plastic scintillator plane (20 x 15 x 3cm^2 x 3m). Ninety-nine of the 176 tons are in the fiducial volume. Energy resolutions quoted are $0.5/\sqrt{E}$ for the hadron showers, 20% for the muons.

2.2 Prompt Neutrino Event Rates

Total event rates. In order to compare the findings in the three detectors[15-17] quantitatively the simplest common event sample criteria are: events with muons (negative or positive) and total hadron energy $E_{HAD} > 10$ GeV, corrected for muon acceptance and detection inefficiencies, and events without muons (i.e. neutral current events due to ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ and events with an e^- or e^+). The rates for these two event categories, called 1-μ-events and 0-μ-events, are given in Table 1, separately for full density and 1/3 density running. Combining the data from the two different density runs and extrapolating linearly to infinite density the corresponding prompt signals are found. Thus the existence of a prompt neutrino flux inducing charged and neutral current events is established independent of conventional background neutrino flux calculations.

See Table I.

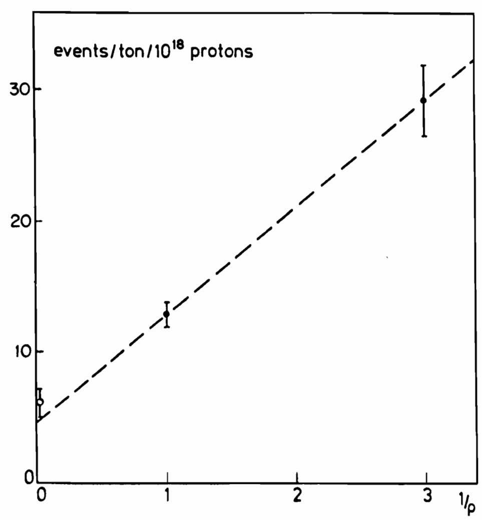
Figure 4) Event samples and their energy distributions as observed in BEBC.



	μ^-	e^-	μ^+	e^+	NC
OBS.:	87→103.2±11.	29±5.3	24.5±5.	10±3.2	53→36.3±7.5
CONV. BKGD:	66.5±7.3	7.1±.8	13.4±1.5	2.2±.24	16.3±1.6
PROMPT:	36.7±13.2	21.4±5.4	11.1±5.2	7.8±3.2	20±.8
Per t_p:	2.5±.9	1.2±.3	.75±.35	.42±.17	1.34±.5

Figure 4 shows a summary of the events with muons, electrons (CC), and no leptons (NC) observed in BEBC, corrected for EMI inefficiencies. The results of the full density runs from 1977 - reasonably compatible with the 1979 data within the (large) statistical errors - are included. The overall NC/CC ratio is 0.35 ± 0.08 (E_{HAD} > 10 GeV). Splitting the NC events into ν_μ and ν_e induced - assuming NC/CC = 0.32 for ν_μ and $\bar{\nu}_\mu$ - yields NC/CC = 0.45 ± 0.40 for ν_e and $\bar{\nu}_e$. The total number of events observed, for a particular target, with energies greater than 10 GeV is essentially independent of the event classification and hence independent of the EMI efficiency, electron detection etc. Figure 5 shows the variation of the total event rate ($e^\pm$, $\mu^\pm$ and NC) as a function of 1/ρ (ρ in units of density of Cu). A linear fit gives a value for the intercept (1/ρ = 0) of 0.46 ± 0.19 prompt events/ton/10^{17} protons. This compares favorably with the value of 0.61 ± 0.11 prompt events/ton/10^{17} protons obtained from the sum of the prompt e^- and e^+, μ^- and μ^+ and NC rates and hence serves as a useful cross-check on the estimate of the conventional neutrino flux.

Figure 5) Total events rates in BEBC as a function of 1/ρ dump.



Prompt electron event rates. The prompt electron event rates are also given in Table 1. For BEBC they are obtained by subtracting the conventional background from the observed number of events (of Fig. 4). For the counter experiments they have to be deduced from the prompt 0-μ-event rates according to

$N(e^+,e^-)_{prompt} = .7 \times [N(0\text{-}\mu)_{prompt} - .32\ N(1\text{-}\mu)_{pr}]$

where the factor 0.32 accounts for the $\bar{\nu}_\mu$ induced neutral current (NC) events and the factor 0.7 for the $\bar{\nu}_e$ induced NC events. The CDHS error is preliminarily overestimated.

Energy distribution of prompt events. The energy dependence of the prompt electron neutrino flux (the mean of ν_e and $\bar{\nu}_e$) is shown in Figure 6a. It is obtained from the electron events in BEBC by determining the prompt e^- and e^+ event rates as a function of energy and assuming values of σ/E (in units of 10^{-38} cm^2/GeV/nucleon) of 0.62 for ν_e and 0.30 for $\bar{\nu}_e$. The flux given corresponds to the very forward direction (< 1.8 mrad) and is the average over the 10 μster. subtended by BEBC. For E_ν > 10 GeV, the total number of prompt ν_e per proton per μster. is (3.7 ± 1.0) x 10^{-8}. Using these data together with an estimate[12] of the number of π^+ mesons produced in proton-copper collisions into the solid angle subtended by BEBC, the ratio of prompt ν_e to π^+ can be determined. This is shown in Figure 6b as a function of energy, together with the prompt μ/π ratio for comparison. The curve for μ/π is a fit to the prompt muon fluxes measured in the shielding (c/o Fig. 2)[12] - $\mu/\pi^+ = 1.5 \times \exp(-0.015 p_\mu)$ - and the two data points are measurements by Kasha et al.[18]

Figure 6. Prompt ν_e flux (a) and ν_e prompt/π^+ ratio (b) as a function of E_Ln. Also shown in (b) is the ratio μ_{prompt}/π^+ as obtained from the μ flux measurements in the shielding (curve) and as measured by H. Kasha et al.[18]

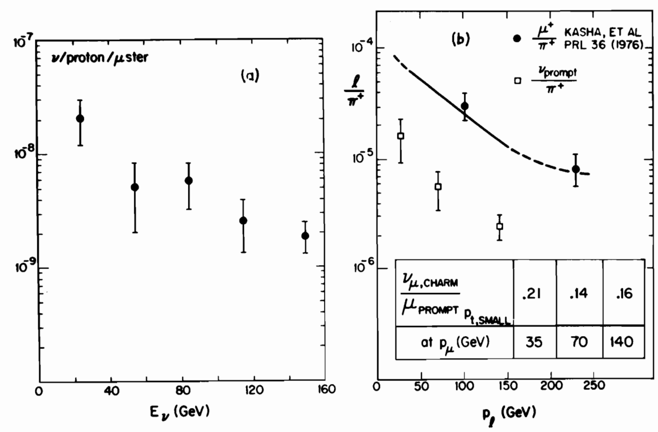


Figure 7 shows the total energy (=E_{HAD} + E_μ) distribution of the prompt μ events in the CDHS detector obtained by extrapolation bin by bin of the 1/3 density and full density data to infinite density[19] and by subtraction of the conventional background[12] from the full density data. Both methods give similar results.

Figure 7. Prompt μ events in CDHS detector, obtained by extrapolation (o) and by subtraction method (x). The histogram indicates ν_μ events from $D_{\mu 3}$ decays (see text).

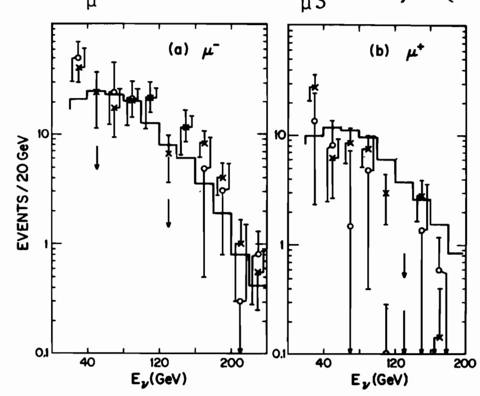
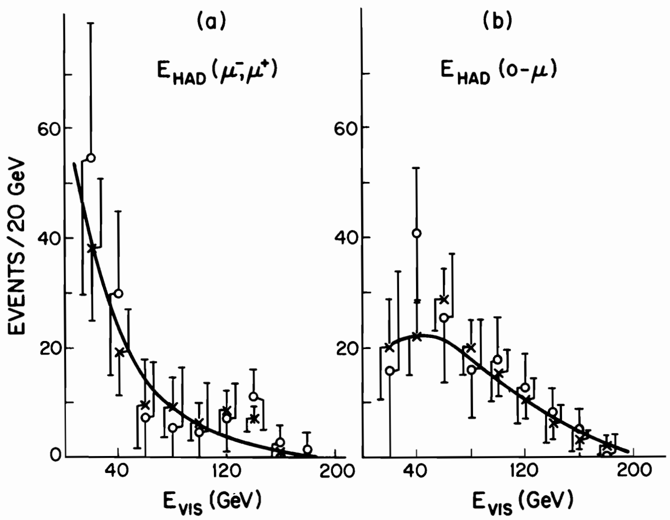


Figure 8(a) shows the hadron energy spectrum of the prompt μ^- and μ^+ events together (muon reconstruction analysis is in progress) and Figure 8(b) the same (i.e. the total energy) for the prompt events without muons.[20]

Figure 8. Hadron energy spectra of prompt CC (a) and 0-μ (b) events from the CHARM beam dump experiment, by extrapolation (o) and by subtraction (x) method.



Also here the results obtained by the extrapolation and subtraction methods are within the large statistical error in agreement. The conventional back round event rates for E_{HAD} > 10 GeV were obtained using the conventional y-distribution and $\sigma^{\nu}/\sigma^{\bar{\nu}}$ = 2.08.

Cross section estimates for D meson production. If the prompt neutrinos are assumed to be due to the semileptonic decay of D mesons produced in proton-copper collisions, cross sections for such production can be estimated making the following additional assumptions:

(i) equal prompt ν_μ, ν_e, $\bar{\nu}_\mu$, $\bar{\nu}_e$ fluxes; possible doubts in the assumption will be discussed below (section 5).

(ii) D mesons of energy E and transverse momentum p_t are produced according to the invariant cross section formula $Ed^3\sigma/dp^3 \sim (1 - |x|)^n \exp(-bp_t)$ with $x = p_L^*/p_{Lmax}$. A value of 3 for the exponent n is consistent with the energy distribution of the prompt events (Fig. 7 and 8). The results are rather insensitive to the parameter b as long as b $\gtrsim$ 1, and b = 2 is assumed here. The variation of the cross section as a function of n and b has been shown earlier.[4]

(iii) Protons re-interact in the dump target with an inelasticity of $\sim$1/3, and the cross section for the ith generation of protons (with energies $(2/3)^i \cdot 400$) varies with $\sqrt{s}$.[21]

(iv) D mesons decay into $K^*e\nu$ and $Ke\nu$ with 5% branching ratio each.

Then, one prompt event above 10 GeV per ton and 10^{18} protons at the position of BEBC corresponds to:

0.9×10^{-3} D's/proton

or $\sigma_{pCu} \to D\bar{D}+\ldots$ = 690 μb[22]

or $\sigma_{pp} \to D\bar{D}+\ldots$ = 11 μb ($\sigma \sim A^1$)

or $\sigma_{pp} \to D\bar{D}+\ldots$ = 30 μb ($\sigma \sim \sigma_{p,abs} \sim A^{.72}$)

With these assumptions and for linear A-dependence the cross sections shown in Table 2 are obtained for various event rates quoted for three neutrino detectors.

These cross section values have additional uncertainities due to the production model (e.g. a factor 1.7 for Δn = 1) and the ignorance of the A-dependence.

See Table 2

3. Beam Dump Type Experiments at Fermilab: Prompt Single Muons

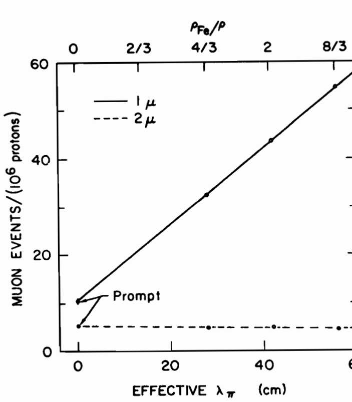
3.1 Experimental Set-Up

The principle of the experiments is to shoot 400 GeV protons at typical intensities of $(3\text{-}5)\cdot 10^5$/sec into a target calorimeter followed immediately by a muon spectrometer and to search for single muons in the final state of the proton interaction. The target calorimeter[23] consists of 45 steel plates, 76 x 76 cm^2, 3.8 cm (the last 25 plates 5.1 cm) thick, each followed by a scintillation counter. The average density is 5.9 g/cm^3, and the plate arrangement can be expanded to 2/3 and 1/2 of that average density. Muons are identified by 10 steel plates (10.2 cm thick) and measured in three toroidal solid iron magnets instrumented with counters and spark chambers giving a $\Delta p/p$ of 10%[24].

3.2 Events with Large p_t Muons

With the muon spectrometer on the beam axis, only muons with $p_{t\mu}$ > 0.8 GeV/c can be measured, due to a 25 cm diameter hole for magnet windings through the center of the toroids. Prompt single muon event rates have been measured by the Caltech-Stanford collaboration with this arrangement [25]. Figure 9 shows how the prompt rates are obtained by extrapolation of the rates measured at different densities of the target calorimter. The raw prompt 1-μ

Figure 9) One - μ^+ and 2-μ-event rates as a function of calorimeter density.

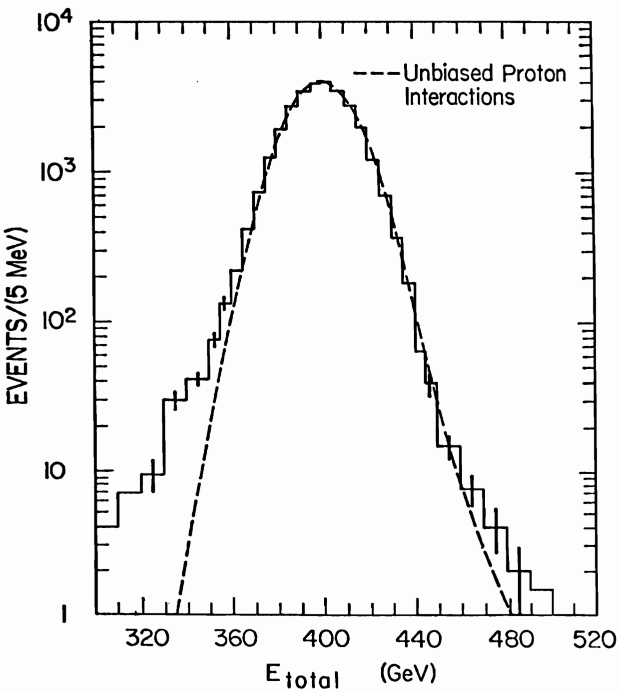


signal of $(10.5 \pm .5)\cdot 10^{-6}$/proton has to be corrected for undetected second muons, $-(10\pm2)\%$, $\pi_{\mu 2}$ and $K_{\mu 2}$ muons from decays downstream of the variable density calorimeters, $-(16\pm6)\%$, and triggers inefficiencies in the expanded dump, $-(20\pm10)\%$. The final rate of $(5.8\pm1.5)\cdot 10^{-6}$/ proton can be attributed to D-mesons making similar assumptions as in the case of the CERN beam dump experiments.

The authors find $\sigma_{D\bar{D}}$ = 31 μb/nucleon for an exponent n=5, and the data consistent range of parameter values allows cross sections varying from 13 to 60 μb.

The same collaboration analyzed the 2-μ-events, the total rate of which is $(5.9\pm0.2)\cdot 10^{-6}$/proton, in terms of total energy, $E_{TOT} = E_{\mu^+} + E_{\mu^-} + E_{HAD}$, and found that (0.76±0.05)% of the $\mu^+\mu^-$ events had less than 355 GeV (Fig. 10)[26]. Less than 10% of these are due to the tail of the Gaussian distribution. Also background (due to π, K decay or catastrophic muon energy loss) is estimated to contribute less than 10%. Hence the most likely explanation is the production and muon decay of a pair of charmed particles with the escaping neutrinos accounting for the energy loss.

Figure 10. Total energy distribution for the $\mu^+\mu^-$ events. The dashed line is the energy distribution for a random sample of proton interactions taken simultaneously with the $\mu^+\mu^-$ data.



The charmed particle ($D\bar{D}$) production cross section can then be calculated under the same assumptions as for single muon events, and a value of (14±5) μb/nucleon is found.

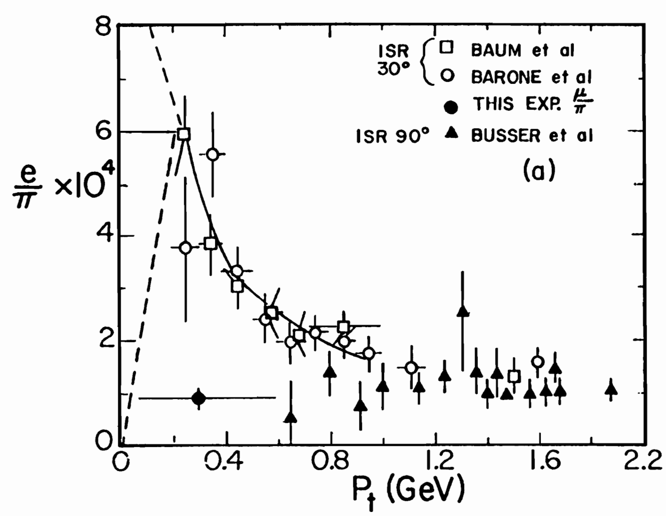
3.3 Events With Low p_t Muons

Early this year the Caltech-FNAL-Rochester-Stanford collaboration ran a test experiment with the toroidal iron magnet displaced by half a radius off-axis in order to measure events with smallest transverse momenta[27]. Also the muon identifier has been modified and consists now of half of the neutrino target used for narrow band experiments: 88 steel plates (5.08 cm thick) with 42 liquid scintillation counters with wave-shifter light collector. This set-up accepts all muons with p_μ down to 8.3 GeV/c. Preliminary results of this test run are:

(i) a prompt single-μ-event rate of $(8.5\pm5)\cdot 10^{-5}$/proton yielding a $D\bar{D}$ production cross section of (17±10) μb/nucleon.

(ii) a prompt μ/π ratio of $(0.83\pm0.13) \times 10^{-4}$ (using the calculated value of 3.55 π's per primary proton interaction) which is much lower than e/μ ratios measured at the ISR in similar p_t and x_F regions[28] (Fig. 11).

Figure 11. e/μ ratios as a function of p_t measured at the ISR and the μ/π ratio measured in the Fermilab beam dump experiment.



In summary, if the prompt muon data from proton-iron collisions are interpreted as being due to $D\bar{D}$ production, the model dependent cross sections range from 13 to 60 μb/nucleon. Applying the same model to single and double μ data one finds (24±6) and (14±5) μb respectively. Assuming $D^+_{\ell 3}$ = 0.14 and $D^0_{\ell 3}$ = 0.02[29] and production ratios of 1:3:3:9 for $D^+D^-:D^+\bar{D}^0:D^-D^0:D^0\bar{D}^0$, the cross sections become (38±9) and (36±13) μb[30].

4. Piminus-Proton Interactions in the BEBC-TST: Prompt Single Electrons

51,000 70 GeV π^- proton interactions in the hydrogen-filled Track Sensitive Target (TST) inside the N_e/H_2 filled BEBC have been inspected event by event for electrons[31]. Every about 30 events a Dalitz pair was found, and 5 events with a single electron in the final state survived all cuts.

The technique of using the TST ($2.4 \times 1.4 \times 1\ m^3$) allows a rather clean analysis of single electron production:

(i) working in hydrogen avoids background due to asymmetric Dalitz pairs by charge balance and minimizes track confusion problems close to the vertex.

(ii) more than 2.5 radiation lengths in the N_e/H_2 mixture (75%, $X^\circ \approx 40$ cm) around the TST identify electrons with good efficiency

(iii) cross section analyses are rather model independent: a 500 MeV electron energy cut allows model modification with less than 5% effect on the result.

Some characteristics of the 5 events with single electrons are shown in Table 3.

See Table 3.

The background due to K_{e3}, $\pi_{\mu 2}$ decays, etc. is estimated to account for 0.7±0.4 events. After background subtraction and cut correction the total prompt electron signal is 11±6 events.

Under assumptions similar to those made in the prompt neutrino and prompt muon data analysis and using a total π^-p cross section of 20.7 mb, a $D\bar{D}$ production cross section $\sigma_{\pi^-p \to D\bar{D}+\ldots} = (23\pm13)\ \mu b$ is found. Furthermore, from the number of final state pions (2.86×10^5), a $e^\pm/\pi^\pm$ ratio of $(0.38\pm0.2) \times 10^{-4}$ is obtained. This is also much smaller than the ISR results[28]; however, the experiments differ in beam energy and particle.

See Table 3.

5. Are D-Mesons the Only Origin of the Prompt Single Leptons?

5.1 Summary of D-Production Cross Sections If All Prompt Leptons Are Due to $D_{\ell 3}$.

Table 4 summarises the present status of cross section results for D production in hadron collisions if the prompt single leptons are assumed to come from $D_{\ell 3}$ decays. The same production and decay model is taken whenever possible. Model variations allow at least a factor 2 of uncertainty in addition to the errors (statistical and systematic) quoted. The data do not yet allow to fix the A dependence of the cross section.

See Table 4.

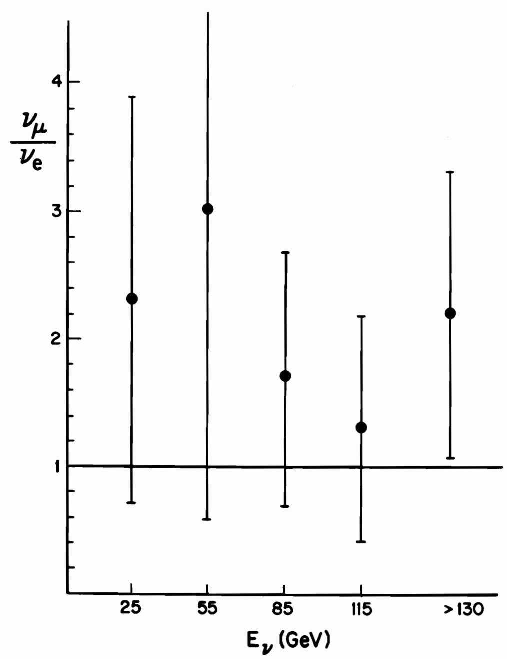
5.2 Antineutrino/Neutrino Ratio

If the prompt leptons come from $D\bar{D}$ production only there must be equal fluxes of neutrinos and antineutrinos. The BEBC data yield a ratio of antineutrino to neutrino events of 0.32±0.14 and the CDHS data 0.35±0.16. The combined ratio of 0.33±0.10 is smaller than the published cross section ratio of 0.48±0.02[34], indicating--albeit with large statistical error--a possible excess of neutrinos. This could be a hint for $\Lambda_c\bar{D}$ production where the Λ_c's are produced with a flat x-distribution--similar to inclusive Λ production[10b,10c]--leading to a relatively large ν acceptance by the detectors. If in addition the Λ_c decay has a smaller Q-value than the D, there would be an excess of lower energy neutrino events compared to an event distribution expected from D neutrinos. Fig. 7 does at least not exclude this fact.

5.3 Electron Neutrino/Muon Neutrino Ratio

The ratio of the number of electron events to the number of muon events observed in BEBC is 0.49±0.17 (0.56 for positive, 0.47 for negative leptons). Figure 12 shows this

Figure 12) The ratio of events with muons to those with electrons as a function of the neutrino energy.



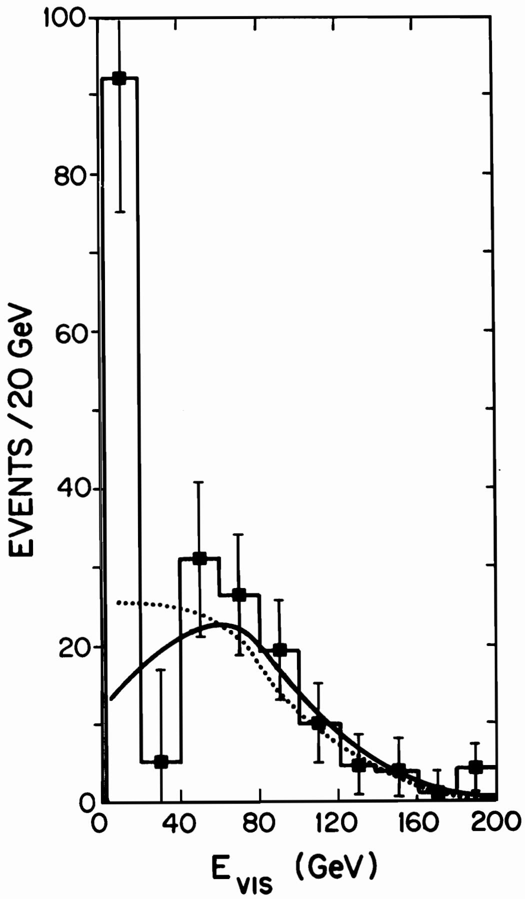
ratio as a function of energy. Using the indirect prompt eletron signal derived from the CHARM data (Table 1) and correcting the prompt 1-μ-event rate for the E_H>10 GeV cut (factor 1.16[20]) an e/μ ratio of 0.59±0.22 is obtained; scaling the CDHS data correspondingly yields 0.34±0.25. The (very preliminary!) combined ratio is $e/\mu = 0.49\pm0.12$. A possible μ-e-asymmetry would open up completely new questions. However, π and K decays are close to 100% μ-e- asymmetric, and a careful scraping monitor analysis must be made before further conclusions can be drawn.

5.4 Too Many Neutral Current Events At Low Energy?

The CHARM collaboration has presented possible evidence that in their beam dump data there are more neutral current events below 20 GeV than can be accounted for by any conceivable known source, including $D_{\ell 3}$ neutrinos[35].

The evidence is deduced from Figure 13 showing the prompt 0-μ-events above 2 GeV obtained from the full-density and 1/3-density run data by subtracting conventional background.

Figure 13. Prompt 0-μ-events above 2 GeV in the CHARM detector during full-density and 1/3-density running. The curve corresponds to $\nu_e(D_{e3})$ induced NC and CC events, normalized to the event number for $E_{vis}>20$ GeV. The dotted curve takes re-interactions of protons into account (see Section 2).



The anomaly is claimed to consist of an excess of 76±16 events in the 2-20 GeV bin. Since the prompt 0-μ-events do not show significant anomaly down to 10 GeV (Figure 8b), the effect--if it exists--must come predominantly from events below 10 GeV. Since, however, the distribution in Figure 13 is not obtained by extrapolation to infinite density, the whole analysis depends critically on how well the conventional background can be estimated and extrapolated down to 2 GeV, where no production data exist and where cascade effects become more and more important. The dotted line in Figure 13 indicates the change of the distribution of D-neutrino events if D-production by the first few generations of protons is added. The significance of the effect depends also critically on muon identification, since--even if pions contribute in this energy region more than estimated--there must be charged current events in excess as well. The bubble chamber data contains many events in the energy region below 10 GeV, many of which have no muon candidate. Making similar extrapolations of conventional and prompt neutrino flux down to ~5 GeV, an "excess" of 25 events in the bin of ~5 to 10 GeV could be deduced, but a proper estimate of neutron background is extremely difficult.

5.5 Hints for τ Neutrinos?

Tau neutrinos are expected to signal themselves by large p_T hadrons in apparent NC events:

$$\nu_\tau + N \rightarrow \tau^- + \text{anything}$$
$$\rightarrow \nu_\tau + \pi^- + \cdots$$

and by large missing transverse momentum in apparent ν_μ or ν_e CC events:

$$\nu_\tau + N \rightarrow \tau^- + \text{anything}$$
$$\rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$$
$$\rightarrow e^- + \bar{\nu}_e + \nu_\tau$$

due to two missing neutrinos, and by a large NC/CC ratio, since the τ is known to decay most of the time into ν_τ and hadrons[36]. If, in addition, the ν_τ's would come from $F \rightarrow \tau\nu_\tau$ decay, those ν_τ's are likely to be lower energetic ($\langle E_{\nu\tau}\rangle \simeq 20$ GeV, about 1/3 of $\langle E_{\nu D}\rangle$). The apparent NC and CC events induced by them would then lead to an excess of prompt NC events with $\langle E\rangle \sim 10$ GeV and of prompt CC events with $\langle E\rangle \sim 20$ GeV. In addition the higher energetic ν_τ from the τ of $F_\tau 2$ would lead to a less visible excess of prompt events over ν_D- events at all energies.

Although the data are still too meager, and theoretical expectations for τ production (either directly or via F decay) are too low it should at least be mentioned that all these features are in the data: In the CHARM events[35] there are three with large missing transverse momentum (1.2±0.2GeV/c) and three quasi-elastic events with large transverse muon momentum; in the BEBC sample there are two such events, and there is the low energy NC effect (section 5.4).

6. Conclusions

The CERN 1979 beam dump experiments have clearly established that the excess neutrino flux discovered in the previous beam dump experiments is due to prompt or short-lived sources created in proton-nucleus collisions. The event rates observed in two runs with different dump densities and extrapolated to infinite density give prompt event rates consistent with those obtained by subtracting the conventional background from the observed event rates.

The most precise number for the magnitude of the prompt neutrino flux comes at present from the 39 e^- and e^+ events observed in BEBC, 9.3 of which were expected from conventional sources. Assuming equal ν_e and $\bar{\nu}_e$ fluxes and $\sigma^{\nu e}/\sigma^{\bar{\nu} e} = 2.08\pm0.09$, a flux of $(3.7\pm1) \times 10^{-8}$ ν_e/(proton x sr) is obtained for E >10 GeV in the forward direction (<1.8 mrad). The ν_e signal extracted from the prompt muonless events of the counter experiments is in agreement with this result.

The rate of prompt single muons measured in the final state of proton-iron collisions at FERMILAB and single electron production in π-proton interactions in the BEBC-TST are in quantitative agreement (within large statistical error) with the prompt neutrino rates.

If all prompt leptons are due to $D_{\ell 3}$ decays, a preliminary cross section analysis yields 15 to 30 μb/nucleon for $D\bar{D}$ production assuming linear A-dependence (or 40 to 85 μb, if the production cross section is proportional to the proton absorption cross section). The data (including the ISR results) do not yet allow to fix the A-dependence.

There are possible hints that not all prompt leptons are from $D_{\ell 3}$ decays, only: (i) The measured ratio of prompt e to prompt μ event rates is 0.49±0.12. (ii) The ν flux could be higher than the $\bar{\nu}$ flux. (iii) At low energy there are more NC events than can at present be accounted for by known sources. (iv) A few events have "anomalously" large transverse momentum hadrons and leptons, some have "anomalously" large missing transverse momentum. The study of these effects requires more analysis of the existing and probably accumulation of more data.

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Discussion

Q. (Cautis, SLAC) You had some data at 1/2 density for the CERN dump. How does it compare with the other 2 measurements?

A. They were only used for the muon flux measurements in the shielding. The neutrino detectors did not run with 1/2 density. Is this the answer? It was only a short test and without neutrino detectors.

Q. (Treiman, Princeton) May I just ask you to repeat your hinted explanations to the eμ ratio?

A. I show the same thing again. At first we don't know at all, right? I was afraid of doing it too consistently. But if it comes from F's, and if the F's decay into $\mu\nu_\mu$ then this automatically leads to μe asymmetry. But if we have μ's (because like pions) they decay only into μ's because of the helicity argument. There is not more to that. Sorry.

Q. (Malcolm Derrick, Argonne) I'd like to emphasize that these beam dump experiments essentially measure multiplicity. They measure the fractional chance of producing a D meson or whatever you are assuming per collision. Now we know from the experiments of Busza and his collaborators that the multiplicity production in the forward direction which is, of course, appropriate to the CERN experiment particularly from complex nuclear targets or from protons is the same. Therefore, it seems to me the way to take into account the A dependence is just to take the multiplicity you measure and multiply by inelastic proton-proton cross section in order to get the final answer. That essentially means that the cross section dependence is closer to $A^{2/3}$ rather than A.

A. We don't know. One of the next beam dump experiments would certainly have to measure the A dependence of the D production.

Q. (Albright, Northern Illinois/Fermilab) Shrock, Smith and I made a study of ν_τ interactions and we found that one of the clearest signals was to look in the single muon channel and check the ϕ angular distribution, the opening angle between the missing neutrino direction and the hadron jet direction. This has peaked very much at 180°. If one makes the cut on $p_\perp$ missing, we found in fact there were no events below 120°. So even though there are only 3 or 6 or 8 events depending on how you count, this may be a very crucial check.

Q. (Winter, CERN) I have a brief comment on Albright's suggestion. If you remember the events I have shown which suggested large missing transverse momentum, you could see that the muon and the hadron always went to only one side with respects to the neutrino beam. And that, of course, implicitly already demonstrates the point of Albright. Namely, that the missing transverse momentum is always opposite to the hadron direction.

Q. (John Ellis, CERN) It seems to me that it's probably rather difficult to explain the apparent violation of μe universality using your suggested 2 body decays of F. Just because the same helicity argument which suppresses e relative to μ, also suppresses μ relative to τ by a factor, if you neglect phase space, of the order 300. That's just m_μ^2/m_τ^2. So it seems to me that if you wanted the difference between the μ decay and the e decay to be responsible for e universality violation, there should be 10 times as many τ decays as the total prompt D signal which you are seeing.

Q. (J.Sandweiss) I wanted to ask you if you had some idea of where that ratio of 1:3:9 came from in the D^0 production?

A. No I cannot. If Bodek is here, he might tell us.

Table 1. Events with $E_{TOT}-E_{\mu} > 10$ GeV

Detector	BEBC		CDHS		CHARM	
fid. mass (tons)	∿13		∿500		∿99	
f(a)	1		0.85		0.81	
dump density	full	1/3	full	1/3	full	1/3
tp(b)	14.9(c)	3.9	273	100	55.3	20.8
1-μ-events	84±9.6	52±7.6	1435±86	1187±95	265±17	220±15
per tp	5.6±0.6	13.4±2	5.3±0.3	11.9±1	4.8±0.3	10.6±.7
prompt	1.8±1.4		1.9±0.7		1.9±0.6	
0-μ-events	62.3±8.9	36.6±7	912±107	649±97	210±17	135±12.5
per tp	4.2±0.6	9.4±1.8	3.3±0.4	6.5±1	3.8±0.3	6.5±0.6
prompt	1.6±1.3		1.7±0.8		2.5±0.5	
0-μ/1-μ	0.74±0.14	0.70±0.17	0.64±0.08	0.54±0.08	0.79±0.07	0.61±0.07
prompt events with e^+ or e^- (per tp)	1.6±0.3		0.8±0.6		1.33±0.35	

(a) Flux dilution factor relative to BEBC due to larger distance from dump
(b) = detector mass (tons) *f* number of protons used (in 10^{18})
(c) 1977 dump data included

Table 2. Preliminary cross section results from the CERN beam dump experiments

From \ in	BEBC	CDHS	CHARM[20]
$\frac{e^- + 2.08e^+}{2}$	11±2.1	7±5 *)	14.5±5.1
$\frac{\mu^- + 2.08\mu^+}{2}$ $E_{TOT}>10$	22±6.4	9.3±4 (by extrap) 14±3 (by subtr) (E_{TOT} > 20 GeV)	29±9 (by extrap) 23±5 (by subtr)

(*) by scaling the CHARM number by the ratio of prompt 0-μ-events (Table 1).

Table 3. Events with single electrons in $\pi^- p$ interactions in BEBC-TST.

Event	1	2	3	4	5
Charged tracks	4	6	8	10	12
Charge of e	−	−	−	+	+
Momentum of e (GeV/c)	19.4	2.5	2.1	5.3	0.72
Transv. mom. of e (GeV/c)	0.37	0.25	0.15	0.59	0.17

Table 4. Cross section summary from hadron induced prompt single lepton data if due to $D_{\ell 3}$.

Reaction	Detector	σ [μb/nucleon]	Remarks
p Cu	BEBC	16.5±6.7	average e,μ result (table 2)
	CDHS CHARM	14±3 23±5	} "subtraction method", μ result
p Fe	CALTEC-STANFORD	20±5	single-μ result (BR=0.1)
pW	MICHIGAN CALORIMETER	30--75	test experiment[32]
p Fe	Serpukhov-ν-detector	5±4	70 GeV protons[33]
π^- p	BEBC-TST	23±13	70 GeV π^-
pp	3-arm-eμ-spectrometer at CERN-ISR[8]	21.9±5	(10.1±2.3)μb per unit of rapidity, $\sqrt{s}$ = 53÷63 GeV