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OBSERVATION OF PROMPT NEUTRINOS

FROM 400 GeV PROTON NUCLEUS COLLISIONS

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ABSTRACT

In 70 000 photos taken in BEBC during an experiment in which the 400 GeV proton beam of the CERN SPS was dumped into a massive Cu target 820 m upstream of BEBC, 70 interactions induced by neutral primaries above 10 GeV were observed. In 11 events the secondary charged lepton is an e^-, in four events an e^+. This number of electron events cannot be due to electron neutrinos from conventional sources (K, Λ, Σ^- decays). The flux of the additional (prompt) neutrinos is evaluated. Possible origins are discussed in terms of charmed particles, τ's, and as yet undiscovered particles. Limits are given on axion production.

A proton beam dump experiment has been performed at the CERN SPS to search for new penetrating neutral particles or neutrinos other than from π, K and hyperon decays. In this type of experiment the secondary π and K mesons are absorbed in a large dense target (dump) so that the flux of neutrinos from conventional sources is reduced by a large factor (some thousands) relative to normal wide-band operation. However, neutrinos produced either directly or in the decay of particles with lifetime $< 10^{-11}$ s (hereafter called prompt neutrinos) would be unaffected.

The experimental lay-out is shown in fig. 1. The 400 GeV/c extracted proton beam of the CERN SPS was directed on to a copper target 27 cm in diameter and 2 m long. A 1 m long block of iron was placed 50 cm downstream of the target and a 3 m block of iron 50 m downstream in order to ensure that any flux of π and K mesons escaping from the dump did not enter the 300 m long decay tunnel. The muon shield consisted of 180 m iron and 170 m rock and earth. During the experiment the fluxes of muons at depths of 10, 30 and 50 m in the iron shield were monitored continuously using solid state detectors distributed over an area of $\sim 2\ m^2$ centred on the beam axis. From the increase of muon fluxes produced by intentionally mis-steering the proton beam into the wall of the vacuum pipe, it was concluded that the beam hit the dump correctly under normal operation.

The bubble chamber BEBC, situated 820 m from the target, was filled with a 72% neon-hydrogen mixture (density 0.66 g/cm^3, radiation length 44 cm). Muons originating in the bubble chamber were identified by the External Muon Identifier (EMI) [1] consisting of two planes of proportional wire chambers of areas 18 m^2 and 150 m^2, respectively. A total of 70 000 photographs were taken corresponding to an integrated intensity of 3.5×10^{17} protons on target. In addition, 14 000 pictures were taken to investigate the background from cosmic rays. The film was scanned twice for any interaction induced by a neutral primary with at least one forward-going secondary of more than 1 GeV/c.

Because of the relatively short radiation length, electrons could be identified by bremsstrahlung or direct pair production with an efficiency > 90% and the high magnetic field (3.5 T) allowed their charge and momentum to be determined. For muons of momentum > 5 GeV/c the geometrical efficiency of the EMI is ∿ 100% and the electronic inefficiency has been determined to be (3 ± 1)%.

Events were retained if they occurred in a fiducial volume of 19 m^3 corresponding to a target mass of 13 t. Events were classified as charged currents $\mu^\pm$ if they contained a $\mu^\pm$ of momentum greater than 5 GeV/c identified in both EMI planes. If the secondary lepton was an electron or positron the event was classified as $e^\pm$ and events with neither muon nor electron were classified as neutral current (NC). A total of ∿ 180 events were found and measured. Fig. 2 shows the energy distributions for the five categories of the 92 events with visible energy E_{vis} > 5 GeV. The 70 events with E_{vis} > 10 GeV were identified as 29 μ^-, 11 e^-, 5 μ^+, 4 e^+ and 21 NC events. Eight NC events below 10 GeV have a μ^- candidate (< 5 GeV/c) and represent the upper limit to the low energy neutrino flux from the nuclear cascade in the dump. One μ^+ event has an e^- of 500 MeV and is the only di-lepton candidate in the sample. In the cosmic ray run no event with leptons and none above 6 GeV were detected.

Some of the characteristics of the observed events were investigated. In fig. 3 are shown the distributions in the variable $y = E_{hadron}/E_{vis}$ for the $\mu^\pm$ and $e^\pm$ events. The μ^- and e^- have approximately flat y distributions whereas the μ^+ and e^+ events have y distributions peaked at small y, compatible with the $(1 - y)^2$ distribution expected for antineutrino events. The ratio of neutral current to charged current events for E_{hadron} > 15 GeV is NC/CC = 0.42 ± 0.17. This is compatible with recently reported by this collaboration from another experiment: $(NC/CC)_\nu = 0.32 \pm 0.03$ and $(NC/CC)_{\bar\nu} = 0.34 \pm 0.07$ [2]. The observed V^0 rates in charged and neutral current interactions are consistent with those found in conventional neutrino experiments. It is concluded from these observations that the majority of the events can be interpreted as normal neutrino interactions.

However, the striking feature is the large number of e^- and e^+ events relative to the number of μ^- events.

The expected ratio of e^-/μ^- events from π and K decay neutrinos can be accurately predicted independent of absolute flux calculations. It is given by the K/π production ratio (0.11), relative Q-values, absorption lengths and branching ratios ($\pi_{\mu 2}$: 1, $K_{\mu 2}$: 0.636, K^+_{e3} : 0.0482, $K^o_{L,e3}$: 0.390, $K^o_{S,e3}$: 0.000672). Assuming the same production spectra for K^o and K^+ a ratio of e^-/μ^- = 0.06 is obtained. The ratio e^+/μ^+ is calculated similarly including Λ and Σ^- decays and is 0.1. These ratios have errors of $\sim$ 10% from uncertainties in the K/π ratio and relative absorption lengths. From those ratios and the observed μ events 1.8 ± 0.4 e^- and 0.5 ± 0.25 e^+ events with E_{vis} > 10 GeV are expected, to be compared with 11 e^- and 4 e^+ events observed (2 e^- events had p_e < 5 GeV/c).

The flux of prompt neutrinos necessary to account for the excess of e^- and e^+ events is calculated using the energy of the events and the charged current cross sections [3], $\sigma_{\nu_e} = \sigma_{\nu_\mu} = 0.6\ E\ 10^{-38}\ \text{cm}^2 = 2.1\ \sigma_{\bar{\nu}_e}$, where E is in GeV. From the known pion flux the ratios ν_e/π^+ are obtained. The results are shown in table 1. These ratios are not in contradiction with prompt muon production experiments [4, 5], where most muons are produced in pairs.

Absolute event rates from π, K, Λ, and Σ^- decays have been calculated replacing the nuclear cascade in the beam dump by a decay path of one absorption length (18 cm for π, 21 cm for K [6]) and using particle production spectra from the thermodynamical model [7] corrected in order to fit available data [8]. The predicted event numbers and spectra are shown in fig. 2. The corresponding muon fluxes agree with the fluxes measured in the shielding when allowance is made for the prompt muons [4]. This indicates that the predicted neutrino event rates are reliable to ±30%.

As can be seen from fig. 2 the observed event rates are consistent with the assumption of equal amounts of prompt ν_μ, $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$ fluxes.

Several possible sources of the observed prompt neutrinos have been considered:

(a) They could be due to the production and semileptonic decay of charmed mesons, $D\bar{D}$, produced in the dump. In order to estimate from the event rates the order of magnitude of the cross section for such D production, several models for production (thermodynamical [7] and phenomenological [9, 10]) have been assumed. For the decay, several modes ($Ke\nu$, $K^*e\nu$, $K\pi\pi\pi e\nu$) have been considered [11]. These calculations show that production rates of (3 to 12) $\times 10^{-3}$ D's per incident proton or cross sections for $pp \rightarrow D\bar{D} + X$ of 100 to 400 μb (based on a total inelastic proton-proton cross section of 33 mb and neglecting cascade effects) are required to account for the observed $e^{\pm}$ events. Such large values appear to be inconsistent with presently available upper limits on charm production in strong interactions: 10-30 μb deduced from searches for the $K\pi$ decay mode in counter experiments [12] and 1.5 μb from a search for any decay mode in an emulsion experiment [13] for the quoted lifetime range 10^{-12} to 10^{-14} s.

(b) The prompt neutrinos could come from the reactions $pp \rightarrow Y_c\bar{D}$ + anything, where Y_c is a charmed baryon. If the charmed baryon production were peaked at large $x (x = P^*_L/P^*_{Lmax})$ as observed for Λ production then a cross section as low as 20 μb could account for the prompt neutrinos. However, the observation that comparable e^- rates/proton have been detected in an experiment(*) at 15 mr to the proton beam, excludes this extreme hypothesis. If the charmed baryons are produced at low x and have a small decay Q-value, then their production cross section could be less than 100 μb.

(c) Prompt neutrinos from the decay of heavy leptons could also account for the characteristics of the observed events, but the production cross section required is of the same order as for charmed particles and this seems unlikely. In the particular case of τ's the production cross sections are predicted to be of the order of a few nanobarns [14]. If however τ's were produced with cross section of ∿ 100 μb, then since $\tau \rightarrow \nu_\tau$ + hadrons has a branching ratio of ∿ 50% [15], this would lead to an anomalously large NC/CC ratio (> 1) which is not observed.

(*) Eight e^- events were observed during the narrow-band antineutrino experiment in BEBC filled with 74% (mol) Ne/H_2 mixture when only positive secondary leptons are expected. Since background is negligible, these e^- events must be attributed to prompt neutrinos from the beryllium target which was struck by 400 GeV protons directed at an angle of 15 mr away from BEBC. Further details will be given in a forthcoming paper.

(d) Light particles (of less than the kaon mass) short-lived and as yet unknown, cannot be excluded as a source for the prompt neutrinos by the data. In this case the production cross section required could be much smaller than in the case of D, depending on the mass, production mechanism and decay modes of these hypothetical particles.

There has recently been considerable interest [16] in the possible existence of a light semi-weakly coupled scalar boson (the axion) which might be necessary to avoid CP violation in the QCD theory of strong interactions. The axion would make π^0-like interactions and in this experiment such interactions would be classified as NC. However, they would differ from true neutrino NC interactions in that the net momentum of the final hadron system transverse to the beam direction (p_T) should be small in contrast to the $\sim$ 2 GeV/c typical of ν interactions. The geometrical acceptance of BEBC for particles produced at the target with the x and p_T distributions of pions is $\sim$ 1%. There is no evidence for an excess of NC candidates with $p_T < 0.5$ GeV/c. This can be used to set a 90% confidence upper limit on the product of production and interaction cross sections of the axion of

$$\sigma_p \sigma_i(\text{axion}) < 2 \times 10^{-67}\ \text{cm}^4,$$

which is $\sim$ 30 times lower than predicted limits [17].

In general, if there exists a neutrino-like particle which gives only NC interactions, there would be no p_T constraint. For such a particle the 90% confidence limit is

$$\sigma_p \sigma_i < 2 \times 10^{-66}\ \text{cm}^4.$$

In conclusion the production of prompt neutrinos in proton-nucleus interactions has been observed. The results indicate equal fluxes of prompt ν_μ, $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$. The production of charmed particle pairs as the source of these neutrinos would require cross sections in the range of 100 to 400 μb. The decay of short-lived light particles of a new type could account for the prompt neutrino flux with smaller production cross sections. Tau leptons as the source are incompatible with the data. The axion with its predicted properties is excluded.

We would like to thank the SPS operating staff for their cooperation in setting up this experiment at short notice and for the excellent performance of the accelerator throughout the run. We are indebted to the BEBC staff for the successful operation of the bubble chamber and to our scanning and measuring staffs for the rapid processing of the film.

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Table 1

Fluxes of prompt neutrinos ν_e and ν_e/π^+ ratios.

$(<\nu_e> = \frac{\nu_e + \bar{\nu}_e}{2}$ after subtraction of background)

E, GeV	10-50	50-90	90-130
$10^{-11} \cdot <\nu_e>$	1.33 ± 0.6	0.83 ± 0.4	0.53 ± 0.2
$10^4 \cdot <\nu_e>/\pi^+$	0.34 ± 0.15	0.17 ± 0.08	0.11 ± 0.05

FIGURE CAPTIONS

Fig. 1 Layout of the CERN SPS proton beam dump experiments.

Fig. 2 Energy distribution of events with $E_{vis} > 10$ (blank squares) and 5 GeV < E_{vis} < 10 GeV (shaded squares) for the five categories μ^-, e^-, μ^+, e^+ and neutral current events. The number of events given are for $E_{vis} > 10$ GeV. The curves are the event numbers (±30%) predicted to be produced by neutrinos from conventional sources (π, K and hyperon decays) which are, for $E_{vis} > 10$ GeV, 21 μ^-, 1.4 e^-, 3.4 μ^+ and 0.3 e^+ events.

Fig. 3 E_{hadron}/E_{vis} distributions of the $\mu^\pm$ and $e^\pm$ events with $E_{vis} > 10$ GeV.

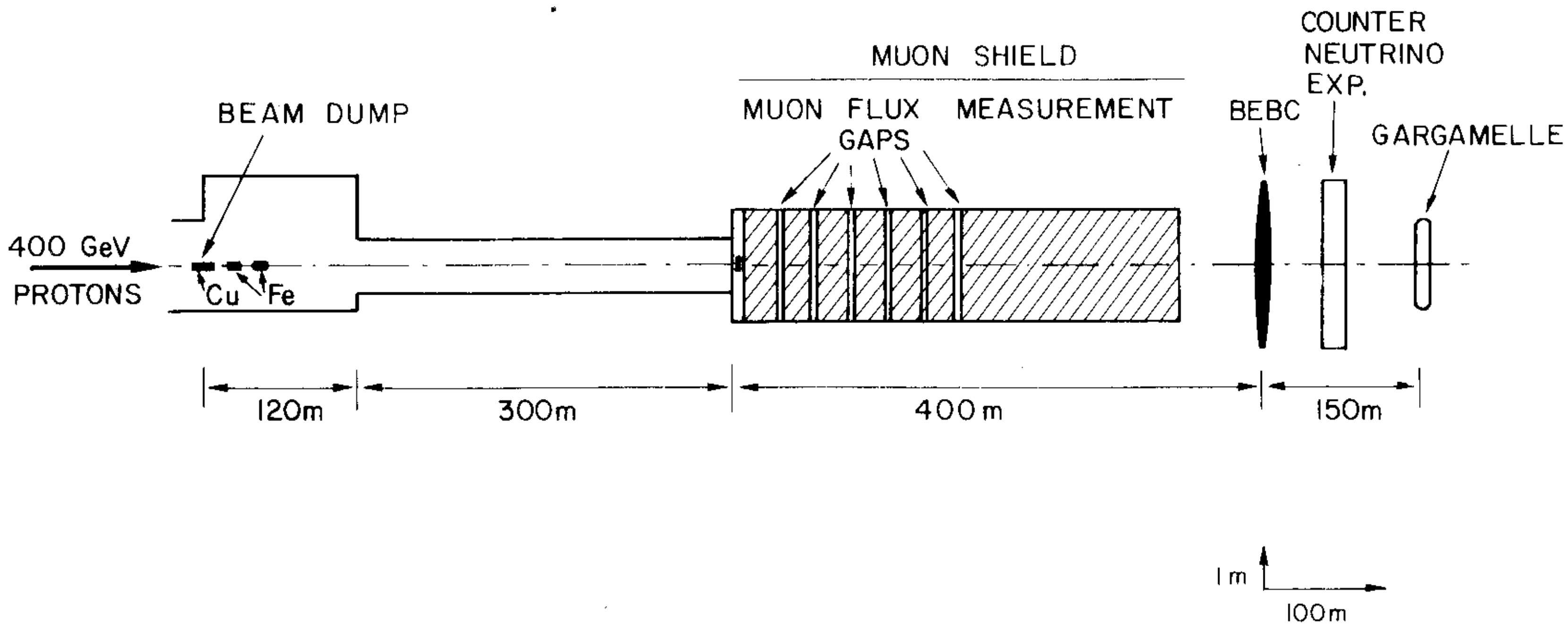
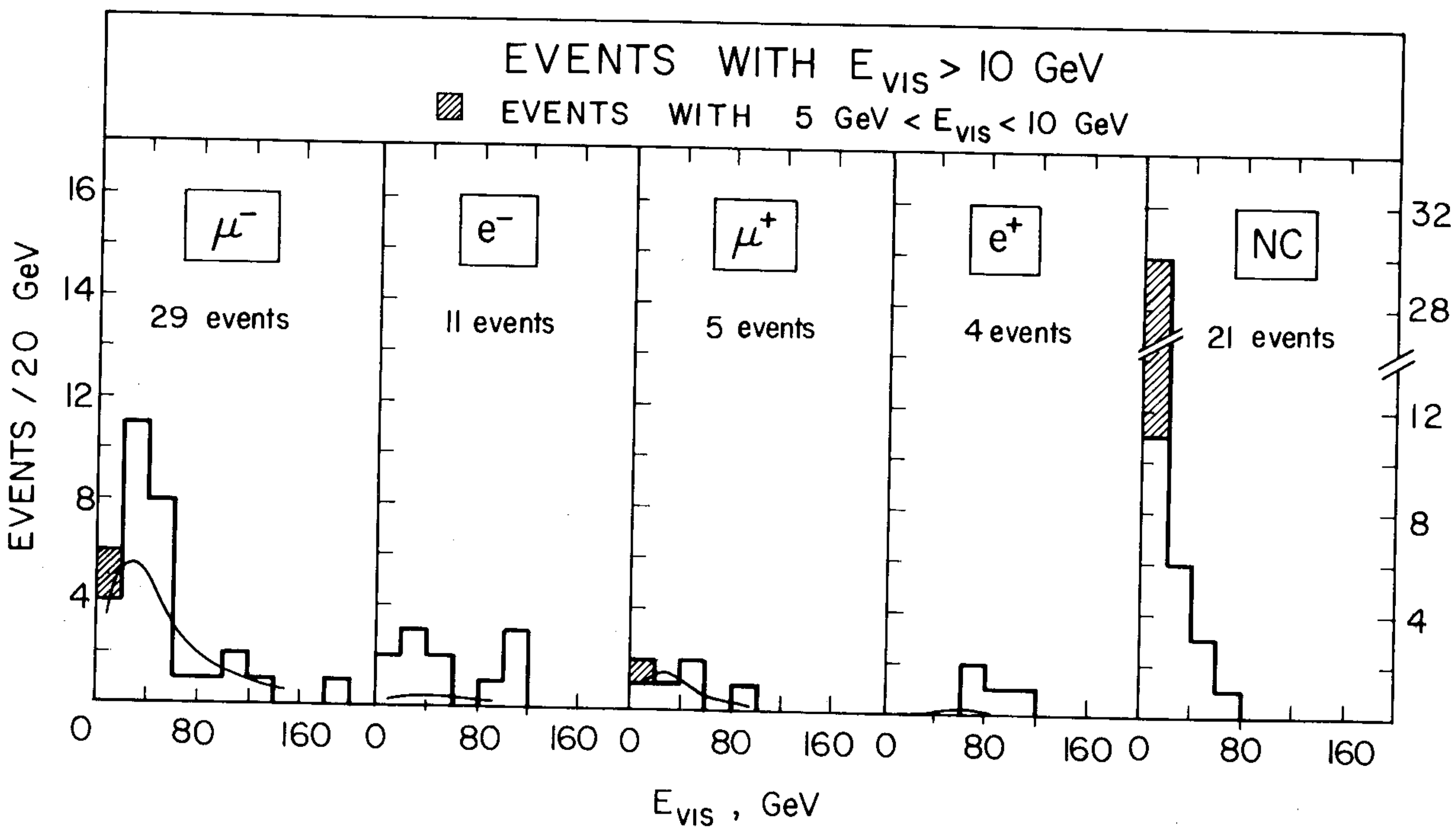
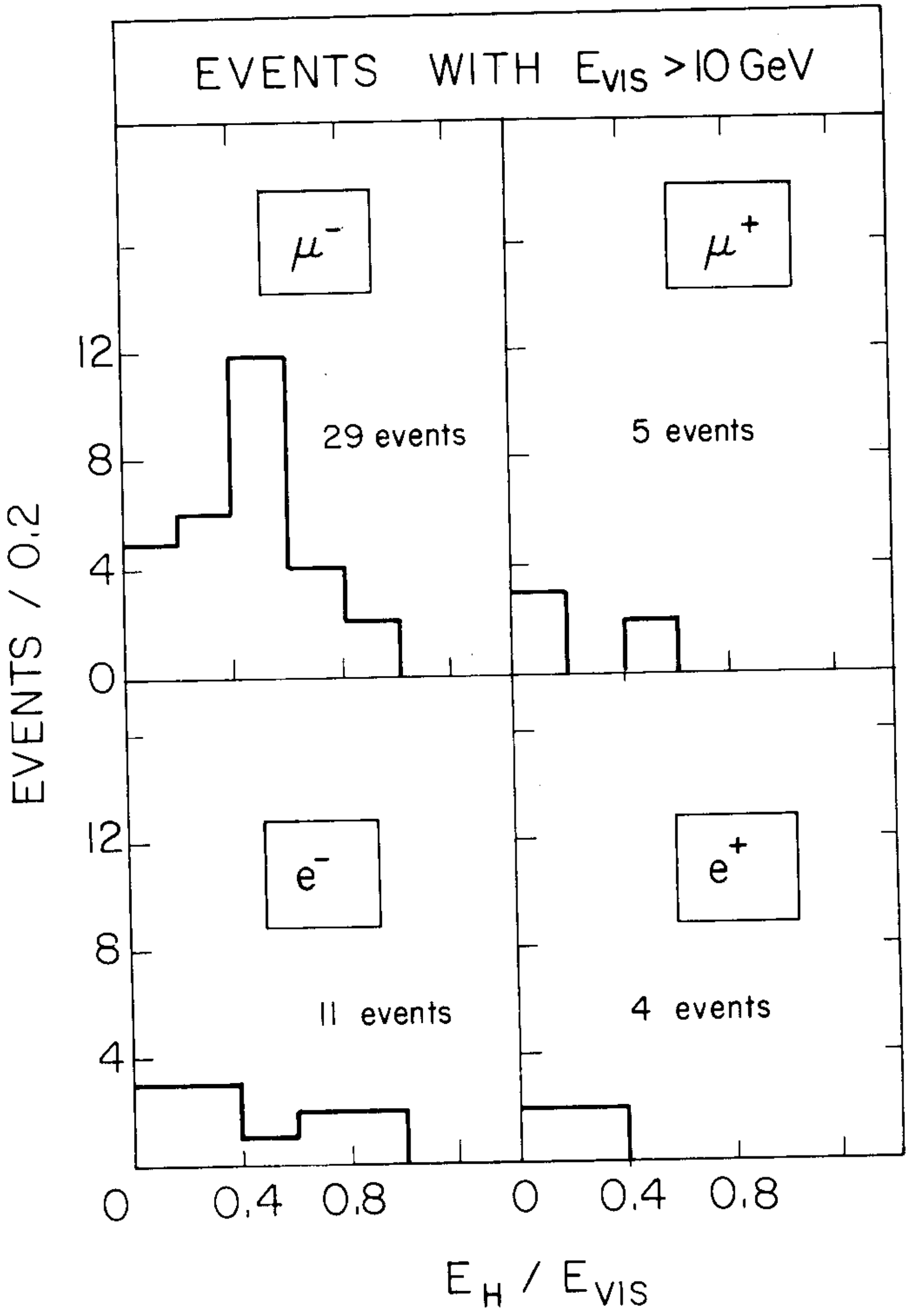

400 GeV
PROTONS
BEAM DUMP
Cu
Fe
MUON SHIELD
MUON FLUX MEASUREMENT
GAPS
BEBC
COUNTER NEUTRINO EXP.
GARGAMELLE
120m
300m
400 m
150m
1 m
100m

Fig. 1


EVENTS WITH E VIS > 10 GeV
EVENTS WITH 5 GeV < E VIS < 10 GeV
μ⁻
29 events
e⁻
11 events
μ⁺
5 events
e⁺
4 events
NC
21 events
EVENTS / 20 GeV
E VIS , GeV
0
80
160
4
8
12
14
16
28
32

<u>Fig. 2</u>



EVENTS WITH E VIS > 10 GeV
μ-
μ+
29 events
5 events
e-
e+
11 events
4 events
12
8
4
0
12
8
4
EVENTS / 0.2
0
0.4
0.8
0
0.4
0.8
E H / E VIS

Fig. 3