

**Experimental study of opposite-sign and same-sign dimuon events
produced in wide-band neutrino and antineutrino beams**

The CHARM Collaboration

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ABSTRACT

We report on a study of 495 ± 32 ν_μ -induced and 285 ± 29 $\bar{\nu}_\mu$ -induced prompt opposite-sign dimuon events, obtained in the CERN Super Proton Synchrotron (SPS) horn-focused beam, using the CHARM neutrino detector. Prompt events are selected using the observed distribution of the distance between the two muons at the vertex. The observed increase of the ratio of prompt dimuon to single muon events with E_{vis} is compatible with the expected behaviour for charm quark production and decay. Assuming the GIM mechanism, we find a strange-sea contribution of 0.050 ± 0.015 , in agreement with our previous result not involving the charm-changing currents.

In the same sample we observed 74 ± 17 ν_μ -induced and 52 ± 13 $\bar{\nu}_\mu$ -induced prompt same-sign dimuon events. On the basis of their kinematics, these events can be well described as being of hadronic origin. The ratios $\mu^-\mu^-/\mu^-\mu^+$ and $\mu^+\mu^+/\mu^+\mu^-$ are found to be 0.14 ± 0.04 (stat.) ± 0.03 (syst.) and 0.18 ± 0.06 (stat.) ± 0.03 (syst.), respectively. The observed ratio $\sigma(\mu^+\mu^+)/\sigma(\mu^-\mu^-) = 0.50 \pm 0.20$ is compatible with the ratio of the single-muon charged-current cross-sections, $\sigma(\bar{\nu}_\mu N \rightarrow \mu^+X)/\sigma(\nu_\mu N \rightarrow \mu^-X) = 0.498 \pm 0.019$.

Opposite-sign dimuon events have been observed in ν_μ and $\bar{\nu}_\mu$ interactions using electronic detectors [1-4] and bubble chambers [5-9], and have been interpreted as coming from the production and subsequent semileptonic decay of charmed mesons [10-11]. According to this interpretation, the charmed quark produced in the elementary processes

$$\nu_\mu + d \rightarrow \mu^- + c \quad \begin{array}{l} \searrow \\ \mu^+ + \nu_\mu + s(d) \end{array} \quad (1a)$$

$$\nu_\mu + s \rightarrow \mu^- + c \quad \begin{array}{l} \searrow \\ \mu^+ + \nu_\mu + s(d) \end{array} \quad (1b)$$

$$\bar{\nu}_\mu + \bar{s} \rightarrow \mu^+ + \bar{c} \quad \begin{array}{l} \searrow \\ \mu^- + \bar{\nu}_\mu + \bar{s}(\bar{d}) \end{array} \quad (1c)$$

gives a D meson in the final state with an energy distribution determined by the fragmentation of the c quark into physical particles. The main features expected for this mechanism are as follows:

- i) The relative rate of dimuon events with respect to events with a single muon in the final state increases with the energy of the neutrino starting at threshold and approaches a constant value.
- ii) In dimuon events induced by antineutrino interactions, the x- and y-distributions of the elementary process (1c) are expected to be significantly different from the distributions observed for single-muon events. The 1μ events are mainly produced off a valence quark, whilst the c quark is produced off the strange sea, which is known to be concentrated at small x-values. Furthermore, the y-distribution decreases for 1μ events, whilst at high energy it is expected to approach a flat y-distribution for 2μ events in reaction (1c).
- iii) The energy distribution of the second muon is related to that of the charmed D meson through the kinematics of the decay process.

Prompt same-sign dimuon events, already seen [4,12,13] in other experiments, have been interpreted as being due to the associated production of a $c\bar{c}$ pair at the hadronic vertex and subsequent semileptonic decay of the c (\bar{c}). Other mechanisms, such as the excitation of heavier quark flavours, may also contribute.

Opposite-sign and same-sign dimuon events were collected using the CHARM neutrino detector exposed to wide-band horn-focused ν_μ and $\bar{\nu}_\mu$ beams at the 400 GeV CERN Super Proton Synchrotron (SPS). A detailed description of the experimental set-up is given elsewhere [14]. The detector consists of a segmented ionization calorimeter having a cross-section of $300 \times 300 \text{ cm}^2$, surrounded by a magnetized iron frame and followed by a muon spectrometer. The calorimeter is a sandwich of marble plates, 8 cm thick, of plastic scintillators, 3 cm thick, 15 cm wide, 300 cm long, and of proportional drift tubes, $3 \times 3 \text{ cm}^2$ in cross-section and 400 cm long. Each marble plate is surrounded by a magnetic iron frame, 45 cm wide and 8 cm thick, and the target calorimeter is followed by four toroidal iron magnets used to analyse the momentum of forward-going muons.

The fine granularity of the calorimeter allows an efficient pattern recognition of the charged tracks of momenta as low as 1 GeV/c (in about 95% of all accepted dimuon events, both tracks are geometrically reconstructed), a good reconstruction of muon track direction [$\sigma(\theta) \simeq 2.5 \text{ mrad}$ for $p > 4 \text{ GeV}/c$], and an accurate determination of the vertex of the hadronic shower [$\sigma(\text{vertex}) < 4.4 \text{ cm}$ for $E_h > 20 \text{ GeV}$].

A sample of opposite-sign dimuon candidates was found, analysing events collected in $\nu_\mu(\bar{\nu}_\mu)$ wide-band beam (WBB) exposures satisfying the following criteria:

- i) The vertex of the shower was required to be in a fiducial volume of $240 \times 240 \text{ m}^2$ cross-sectional area and extending from plane 3 to plane 55 of the calorimeter (corresponding to a fiducial target weight of 77 tons).
- ii) Two penetrating tracks were found by automatic pattern recognition.
- iii) Of the two tracks, one (defined as the leading muon) was required to have a reconstructed momentum with the sign expected from the nature of the beam (μ^- for ν_μ , μ^+ for $\bar{\nu}_\mu$) and with momentum

$p > 4 \text{ GeV}/c$. The $\bar{\nu}_\mu$ contamination of the ν_μ beam is estimated, using 1μ events, to be about 9% in this sample. The ν_μ event contamination in the $\bar{\nu}_\mu$ beam is more important and was reduced by the rejection of all those events in which the second muon had more than twice the energy of the leading muon; the expected contamination after this cut is of the order of 4%.

- iv) A minimum momentum of $4 \text{ GeV}/c$ was required for the non-leading track. If the momentum of non-leading μ was not reconstructed, its sign was assumed to be opposite to that of the leading muon; the fraction of unidentified prompt same-sign events in this sample is smaller than 2%.

An eye scan of the selected candidates was made in order to reject background due to random superposition of two different events occurring in the time gate of the trigger and due to punch-through hadrons, i.e. events in which one of the tracks showed a shower at the end of its range. Trimuon event candidates having a momentum of the third muon above $1 \text{ GeV}/c$ were rejected during the scan. The number of candidates after this selection is 769 (467) for ν_μ ($\bar{\nu}_\mu$) beam exposures.

A correction has been applied for the efficiency of muon pattern recognition as a function of hadronic energy and of the momentum of the second muon. It was evaluated, using Monte Carlo techniques, to be typically 95%. The corrected number of events becomes 798 for ν_μ and 491 for $\bar{\nu}_\mu$.

The main background of dimuon events is due to charged-current events with a non-prompt muon originating from a pion or kaon decay in flight. In previous experiments this background has been evaluated using Monte Carlo calculations [4-9] or by using different target densities [1-2].

In the present experiment, the projected distance between the two muons, Δz and Δy , on two orthogonal axes in the plane perpendicular to the beam direction, and which contains the hadronic vertex, was used to separate prompt events, such as those produced by D-decay, from non-prompt π and K decays.

Muons from the decay of short-lived particles, such as D-mesons, are called "prompt", and extrapolate to the vertex of the hadronic shower within a resolution which is dominated by multiple Coulomb scattering in the material of the calorimeter. Pions and kaons, on the other hand, may be produced either directly at the vertex—in which case, muons from their decay are almost indistinguishable from promptly produced muons—or during the development of the hadronic cascade—in which case the decay muons do not extrapolate, in general, to the shower vertex.

In order to separate the "prompt" signal from the π , K decay background, the shapes of the Δy , Δz distributions for these two components must be known. Since the shapes depend on the fractional momentum z [$z = p_{\mu 2}/(E_h + p_{\mu 2})$] of the non-leading muon, the analysis was done separately for the three z -regions: $z < 0.1$, $0.1 < z < 0.2$, and $z > 0.2$. Figure 1a shows the data sample of neutrino-induced opposite-sign dimuon events with $z > 0.2$. The separation into signal and background is described below.

The distribution of the projected distances of prompt events was obtained by replacing, in all observed dimuon events (both prompt and non-prompt), the two muon tracks by two computer-generated tracks emerging from the shower vertex with the same angle and momentum, in which the known effects of multiple scattering and energy loss in the calorimeter were simulated by Monte Carlo techniques. These pseudo-events were then reprocessed by the analysis program, and the resulting distribution in projected distance at the vertex was taken to represent the prompt events. This procedure, which includes the true masking of the early part of the muon tracks by the hadron shower, also yielded the 95% efficiency for finding both muons by the automatic pattern recognition which was quoted above. The resulting distribution is shown in fig. 1b, compared with the final signal of prompt events for $z > 0.2$.

At the energies relevant to this experiment, the muons from π and K decay deviate very little from the parent hadron direction. Thus the distribution of the expected projected distances Δz and Δy of muons from π and K decay was derived from a sample of known hadron tracks, namely 891 identified punch-through particles. A punch-through particle was defined as a track leaving the hadron shower and interacting after having traversed at least 12 planes of the calorimeter, with visible energy larger than 2 GeV , as observed from the shower produced by the interaction. The distribution of the projected distances for muons from π , K decay for the three z -regions was obtained by weighting the distributions obtained for the punch-through events by the decay probability, assuming them to be all pions. Figure 1b shows the shape of the Δz , Δy distributions thus obtained. It must be stressed that this distribution includes the correct mixture of pions produced directly at the vertex and pions produced in the hadronic cascade.

Thus from the experimental data we know the shape of the Δz , Δy distributions for muons from π and K decay, and we know the shape of the Δz , Δy distributions for prompt muons from the pseudo-events. The continuous line in fig. 1a is the result of the best fit by the sum of these two components, in which the free parameter is the fraction η of prompt dimuon events. The dashed line shows the background distribution normalized to the number of events obtained by the fit. For the total ν_μ sample, the fit gives $\eta = 0.62 \pm 0.04$, corresponding to 495 ± 32 prompt events, and for the $\bar{\nu}_\mu$ sample $\eta = 0.58 \pm 0.06$, corresponding to 285 ± 29 prompt events.

To obtain distributions of these prompt events in the kinematic variables E_{vis} , x , and y , the distributions of the background measured at large distances (where the prompt signal is negligible) were subtracted, after normalization to the number of background events obtained by the fit. The sample of punch-through events was used to check that these distributions are representative for all non-prompt events.

In the same ν_μ ($\bar{\nu}_\mu$) WBB exposures, 271,000 (215,000) single-muon events were found in the fiducial volume with hadronic energy above 2 GeV and muon momentum above 4 GeV/c. The systematic uncertainty of these numbers relative to the number of dimuon events is estimated to be $\sim 5\%$.

Figures 2a and 2b show the relative rate of prompt 2μ and 1μ events for the ν_μ and the $\bar{\nu}_\mu$ beam, respectively, as a function of the total visible energy. The solid line is the expected distribution, obtained by assuming a production model for c quarks, in which the threshold effects are taken into account by using a redefined value of x ("slow rescaling" variable),

$$x' = x + m_c^2/(s \cdot y), \quad (2)$$

where $m_c = 1.5$ GeV.

The x -distribution of valence quarks was parametrized as

$$f(x) = \sqrt{x}(1-x)^{3.5}, \quad (3)$$

and that of strange-sea quarks was parametrized as

$$f(x) = (1-x)^\beta. \quad (4)$$

The value of β was obtained fitting the Monte Carlo predictions to the experimental data; the result is

$$\beta = 7.0 \pm 1.0(\text{stat.}). \quad (5)$$

Figures 3a and 3b show the y -distributions of prompt opposite-sign dimuon events induced by ν_μ and $\bar{\nu}_\mu$, respectively, corrected for resolution, efficiencies, and acceptance criteria. We note that the y -distributions of ν_μ - and $\bar{\nu}_\mu$ -induced dimuon events have very similar shapes, in sharp contrast to the characteristic difference of the shapes for the single-muon final state. A simple comparison of the shapes of the dimuon and single-muon differential cross-sections was made by parametrizing them as

$$d\sigma/dy = A[a + (1-a)(1-y)^2]f(y), \quad (6)$$

where $f(y)$ describes the threshold behaviour of 2μ events folded with the neutrino spectrum. Fitting eq. (6) to the $\bar{\nu}_\mu$ differential cross-section yielded a value of the shape parameter of $a(\bar{\nu}_\mu) = 0.85 \pm 0.10$, in agreement with the expectation of $a(\bar{\nu}_\mu) = 1.0$, for the charm-changing reaction (1c), and in contrast to the normal charged-current distribution which yielded a value of $a = 0.16 \pm 0.01$. If we assume that reaction (1c) is described by the Glashow-Iliopoulos-Maiani (GIM) mechanism [15], the cross-section of that reaction is then determined by a single parameter, the fractional momentum-weighted strange-quark content in the nucleon $\int xs dx / \int x dx$. For $E_{\text{vis}} > 60$ GeV we find a value of 0.050 ± 0.015 , in agreement with previous findings [16] and with our result obtained from a study of $d\sigma/dy$ of charged-current ν_μ and $\bar{\nu}_\mu$ reactions which

yielded a value of 0.06 ± 0.04 [17]. The agreement of these values constitutes a quantitative check of the GIM mechanism.

In the same data sample we obtained 174 ($\mu^-\mu^-$) candidates in the ν_μ beam exposure and 107 ($\mu^+\mu^+$) candidates in the $\bar{\nu}_\mu$ exposure with $p_{\mu_2} > 4$ GeV/c. This was done using the criteria described before and after correction for the efficiency of the pattern recognition procedure. The second muon in this sample of events was also required to give a good fit through the magnetic spectrometer. The application of this requirement to the sample of opposite-sign dimuons reduced the number of prompt events to 424 ± 33 in the ν_μ sample and 233 ± 25 in the $\bar{\nu}_\mu$ sample. Separating the prompt events from the background events on the basis of the observed distributions of the projected distance between the two muon tracks at the vertex, we find 74 ± 17 ($\mu^-\mu^-$) events, corresponding to a fraction of prompt events of $\eta = 0.41 \pm 0.10$ and 52 ± 13 ($\mu^+\mu^+$) events corresponding to $\eta = 0.48 \pm 0.12$ *).

To compare event rates of same-sign and of opposite-sign dimuons, a correction has been applied for the different efficiencies of fitting focused and defocused muons, $\varepsilon = 0.82 \pm 0.15$, and the subsample of opposite-sign dimuon events with both muons fitted in the spectrometer is used. The ratios of prompt events, averaged over E_{vis} , are:

$$\begin{aligned} R(\nu_\mu) &= N(\mu^-\mu^-)/N(\mu^-\mu^+)\varepsilon = 0.14 \pm 0.04 \text{ (stat.)} \pm 0.03 \text{ (syst.)}, \\ \bar{R}(\bar{\nu}_\mu) &= N(\mu^+\mu^+)/N(\mu^+\mu^-)\varepsilon = 0.18 \pm 0.06 \text{ (stat.)} \pm 0.03 \text{ (syst.)}. \end{aligned} \quad (7)$$

The systematic errors of these ratios are mainly due to uncertainties in the shape of prompt and non-prompt distributions. The ratio $R(\nu_\mu) = N(\mu^-\mu^-)/N(\mu^-)$ is plotted as a function of E_{vis} in fig. 4, and compared with results of previous experiments [19] on same-sign dimuons. We note reasonable agreement, although different methods of separating prompt from non-prompt dimuon events were used, and observe an increase of $R(\nu_\mu)$ with E_{vis} . Above $E_{\text{vis}} = 200$ GeV the statistics of this experiment are not significant. A prediction based on a first-order QCD calculation of $c\bar{c}$ production by gluon bremsstrahlung gives a result about a factor of 30 below the experimental data for $p_{\mu_2} > 10$ GeV/c [20] and is shown in fig. 4 as a dotted line. Despite this discrepancy, which may be due to neglecting higher-order QCD corrections, the data show kinematic features which are characteristic of the hadronic origin of the second, same-sign muon.

In table 1 we summarize some average kinematic quantities for same-sign and opposite-sign dimuon events and for single-muon events. Some general conclusions [20, 21] can be drawn from a comparison of these quantities. The second muon can carry only a limited amount of momentum out of the production plane, $p_T^{\text{out}} < 0.5 m_q c$, where m_q is the mass of the decaying quark or hadron. A comparison of same-sign and opposite-sign dimuon topologies shows no increase of p_T^{out} for same-sign events, thereby eliminating the possibility of heavy quarks or heavy leptons contributing strongly to the signal. If a heavy quark would decay via a cascade process, p_T^{out} would, however, be reduced and this conclusion would be less compelling. Heavy-lepton decay events would give smaller energy transfer to the hadronic vertex E_h because of the threshold behaviour, and the azimuthal angle $\phi_{\mu\mu}$ between the two muons would be almost isotropic — features which are not observed.

The origin of the same-sign events can be further studied by a comparison of the value \bar{x}_{vis} . We find \bar{x}_{vis} of these events comparable to the value for single-muon events, both for ν_μ - and $\bar{\nu}_\mu$ -induced events, and larger than for opposite-sign dimuon events, in particular for $\bar{\nu}_\mu$ -induced events. This feature is expected if the second muon originates from the hadronic vertex, especially from the decay of a short-lived particle i.e. from associated $c\bar{c}$ production.

*) The ratio of the background of same-sign and opposite-sign dimuon events averaged for ν_μ and $\bar{\nu}_\mu$ is found to be 0.36 ± 0.06 , in agreement with the observations in bubble chambers and with a Monte Carlo simulation [18] of the hadronic cascade in the calorimeter.

In fact we observe a ratio of cross-sections (uncorrected for the cut $p_{\mu_2} > 4 \text{ GeV}/c$) of

$$\sigma(\bar{\nu}_\mu N \rightarrow \mu^+ \mu^+ X) / \sigma(\nu_\mu N \rightarrow \mu^- \mu^- X) = 0.50 \pm 0.20, \quad (8)$$

which can be compared with the ratio for the single-muon charged-current cross-sections [22],

$$\sigma(\bar{\nu}_\mu N \rightarrow \mu^+ X) / \sigma(\nu_\mu N \rightarrow \mu^- X) = 0.498 \pm 0.019. \quad (9)$$

In summary, this experiment has given a quantitative comparison of new high-statistics data on opposite-sign dimuon events produced by ν_μ and $\bar{\nu}_\mu$ with the GIM mechanism of charm-changing currents. The agreement is very satisfactory for the bulk of the events. A large sample of prompt same-sign dimuon events induced by ν_μ and $\bar{\nu}_\mu$ has been found, giving convincing evidence for the existence of these processes. The rate of these events, as compared to that of opposite-sign dimuon events, is 0.14 ± 0.04 (stat.) ± 0.03 (syst.) and 0.18 ± 0.06 (stat.) ± 0.03 (syst.) for ν_μ and $\bar{\nu}_\mu$, in sharp contrast to the expectation from $c\bar{c}$ associated production by gluon bremsstrahlung. Comparison of some kinematic quantities of ν_μ - and $\bar{\nu}_\mu$ -induced events of different topologies points to features which are consistent with the origin of the second same-sign muon being from the hadronic vertex and with $c\bar{c}$ associated production as a possible source.

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Table 1

Comparison of kinematic quantities of different event topologies
after correction for background ($p_\mu > 4 \text{ GeV}/c$)

Beam	v_μ			\bar{v}_μ		
	$\mu^-\mu^-$	$\mu^-\mu^+$	μ^-	$\mu^+\mu^+$	$\mu^+\mu^-$	μ^+
$\langle E_{\text{vis}} \rangle (\text{GeV})^{\text{a)}$	94.5 ± 7.0	98.1 ± 3.5	60.2 ± 2.2	72.5 ± 17	77.5 ± 4.1	46.0 ± 1.0
$\langle E_{\text{h}} \rangle (\text{GeV})$	50 ± 5	38 ± 1.3	21.8 ± 0.9	23.8 ± 2.8	28.5 ± 1.5	15.1 ± 0.4
$\langle p_{\text{T}}^{\text{out}} \rangle (\text{GeV}/c)^{\text{b)}$	0.30 ± 0.04	0.40 ± 0.02		0.34 ± 0.03	0.50 ± 0.05	
$\langle \phi_{\mu\mu} \rangle (\text{deg})$	128 ± 8	139 ± 2		149 ± 7	137 ± 2	
$\langle x_{\text{vis}} \rangle^{\text{c)}$	0.25 ± 0.03	0.21 ± 0.01	0.24 ± 0.01	0.21 ± 0.03	0.15 ± 0.01	0.21 ± 0.01

a) $E_{\text{vis}} = E_{\mu_1} + (E_{\text{h}} + E_{\mu_2})$

b) $p_{\text{T}}^{\text{out}}$ is the transverse momentum of the second muon relative to the production plane.

c) $x_{\text{vis}} = [2E_{\mu_1}E_{\text{vis}}(\sin^2\theta_{\mu_1}/2)]/[m(E_{\text{h}} + E_{\mu_2})]$.

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FIGURE CAPTIONS

- Fig. 1: Distribution of the projected distance between the two muons in a plane perpendicular to the beam at the hadron vertex:
- As observed in the neutrino beam. The continuous line is the result of the best fit of this distribution by the sum of prompt and non-prompt contributions with shapes as shown in fig. 1b. The fit determines the fraction of prompt events. The dashed line shows the non-prompt background contribution to the observed distribution.
 - For prompt D decay events (●) and for non-prompt π, K decay events (dashed line) as determined in this experiment. The background curve is normalized to the peak to show the difference in the height of the tails.
- Fig. 2: Dependence on E_{vis} of the observed ratio of opposite-sign dimuon events to single-muon events for a) ν_μ and b) $\bar{\nu}_\mu$ with $p_{\mu_2} > 4 \text{ GeV}/c$. The curves shown are obtained by Monte Carlo simulation assuming the Glashow-Iliopoulos-Maiani (GIM) mechanism and describing the threshold behaviour by slow rescaling in $x' = x + m_c^2/(s \cdot y)$, with $m_c = 1.5 \text{ GeV}$. For $E_{\text{vis}} > 60 \text{ GeV}$ we find a fractional strange-quark content of the nucleon of 0.050 ± 0.015 .
- Fig. 3: Differential cross-sections $d\sigma/dy$ of ν_μ - and $\bar{\nu}_\mu$ -induced opposite-sign dimuon events, corrected for resolution and acceptance criteria. The $\bar{\nu}_\mu$ distribution is characterized by a shape parameter $\alpha = 0.85 \pm 0.10$, in agreement with the expectation of $\alpha = 1$ and in contrast to the single-muon distribution, which has $\alpha = 0.16 \pm 0.01$. The dashed lines show the expected distributions and their threshold behaviour.
- Fig. 4: Dependence on E_{vis} of the ratio of same-sign dimuon to single-muon charged-current cross-sections induced by ν_μ from this experiment ($p_\mu > 4 \text{ GeV}/c$) and from previous experiments [19]. The dotted line is a Monte Carlo prediction [20] of associated $c\bar{c}$ production by gluon bremsstrahlung for $p_{\mu_2} > 10 \text{ GeV}$.

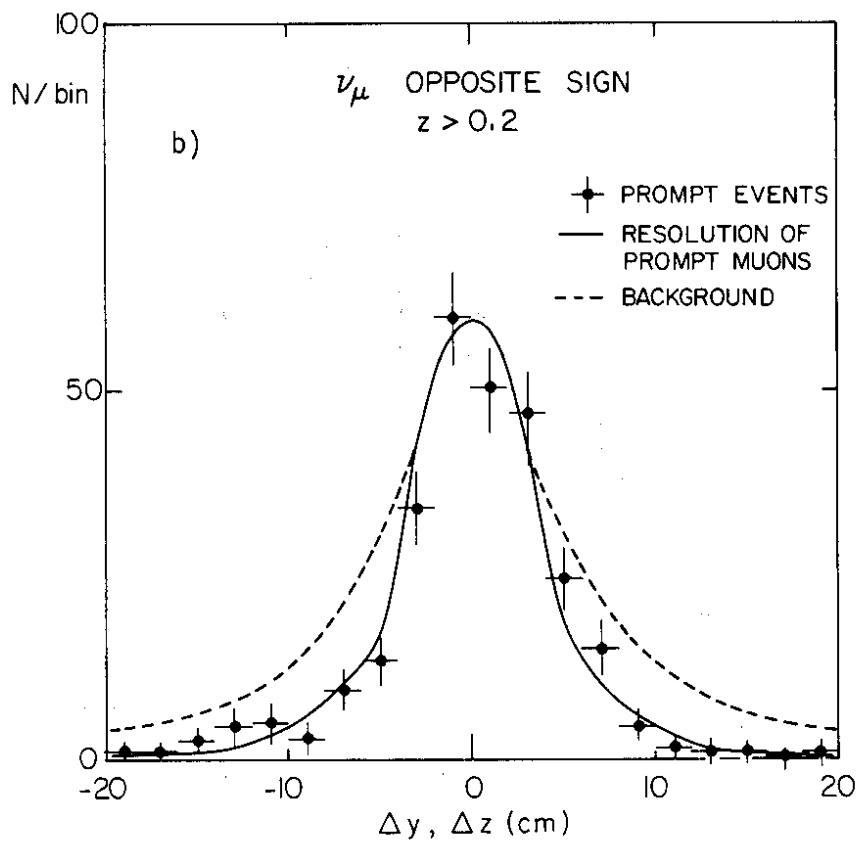
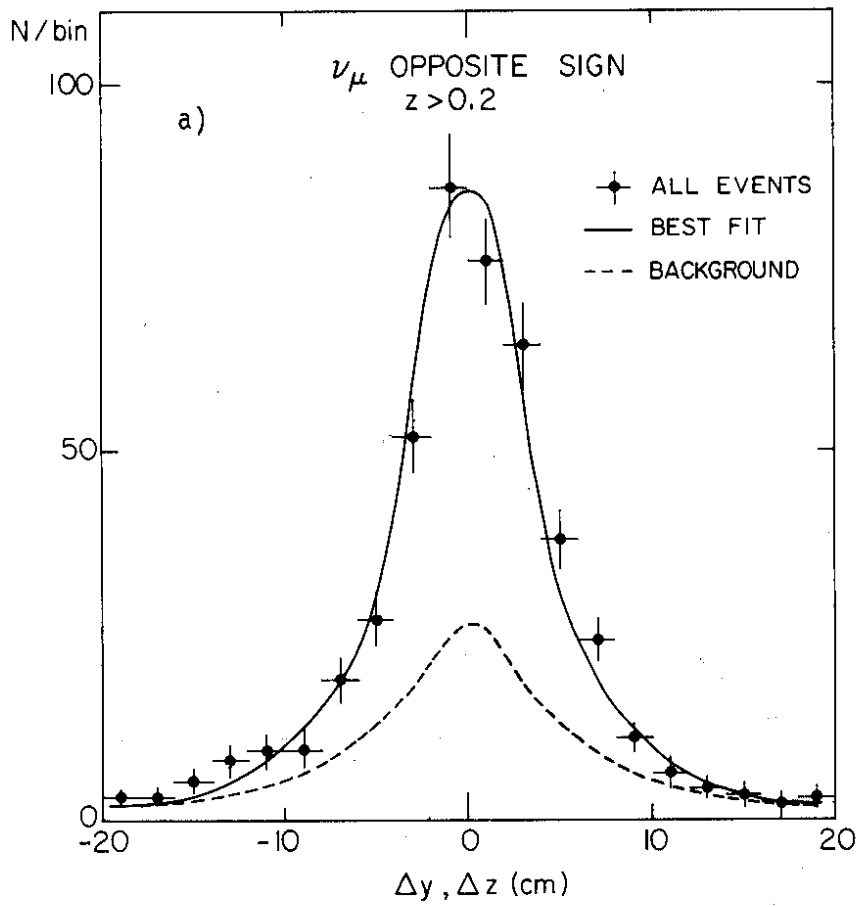


Fig. 1

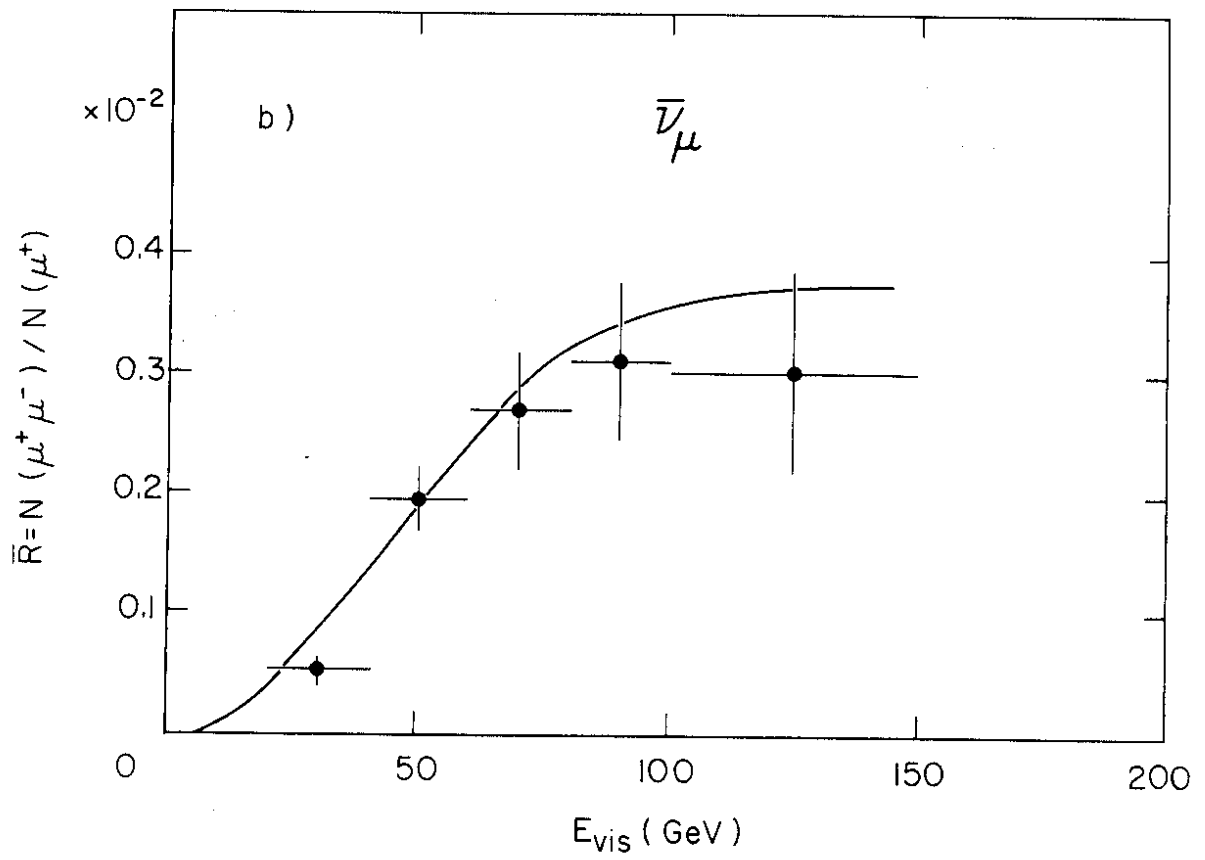
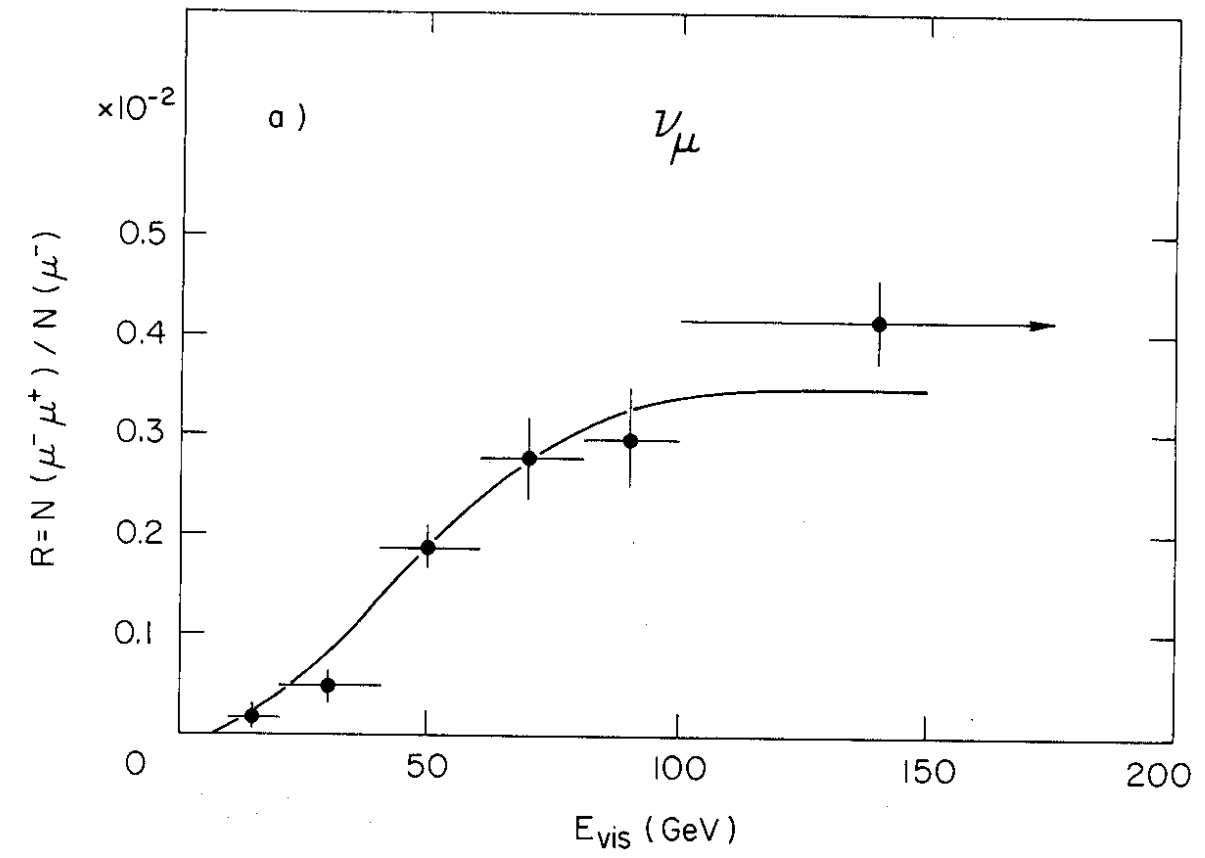


Fig. 2

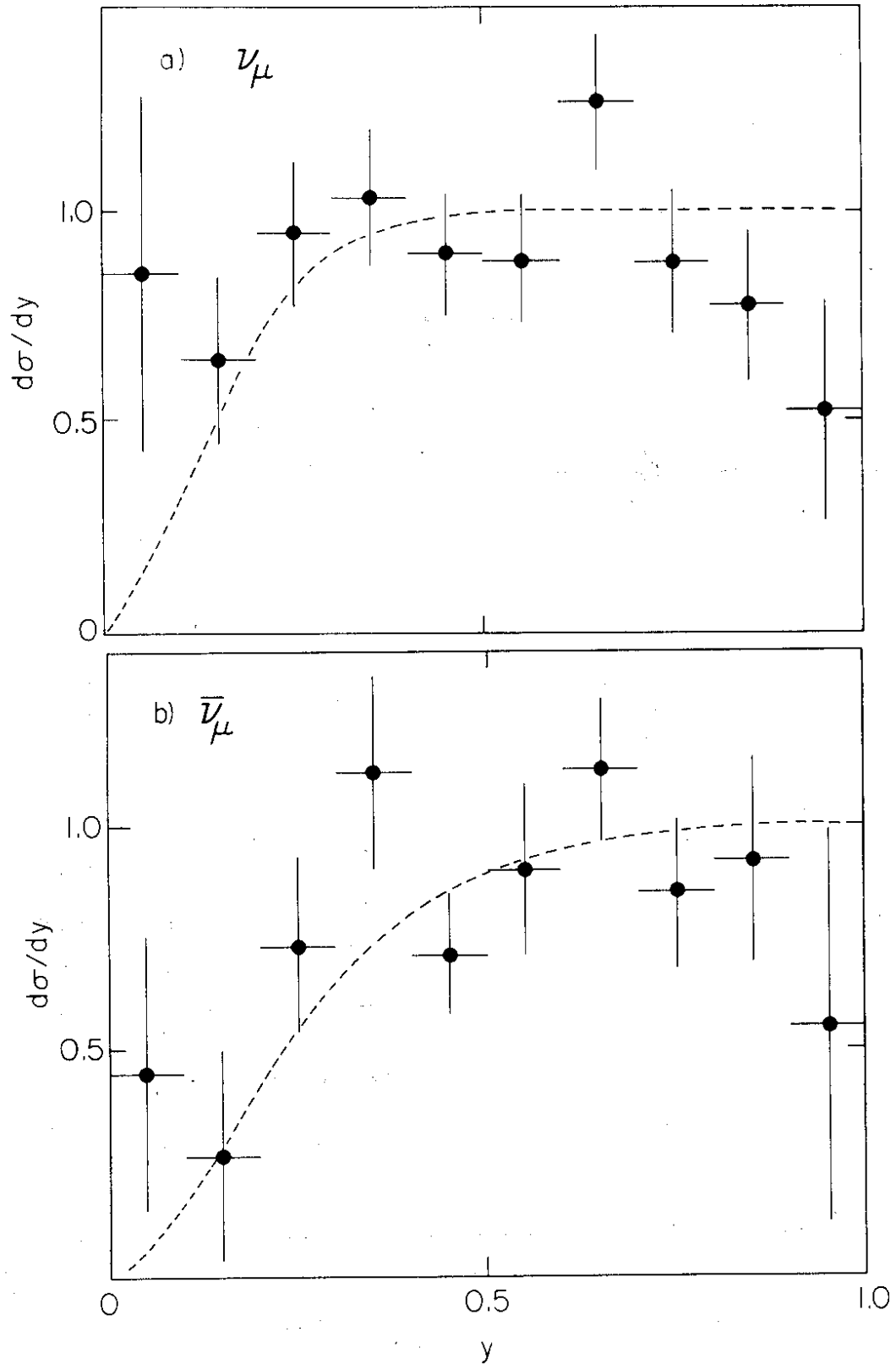


Fig. 3

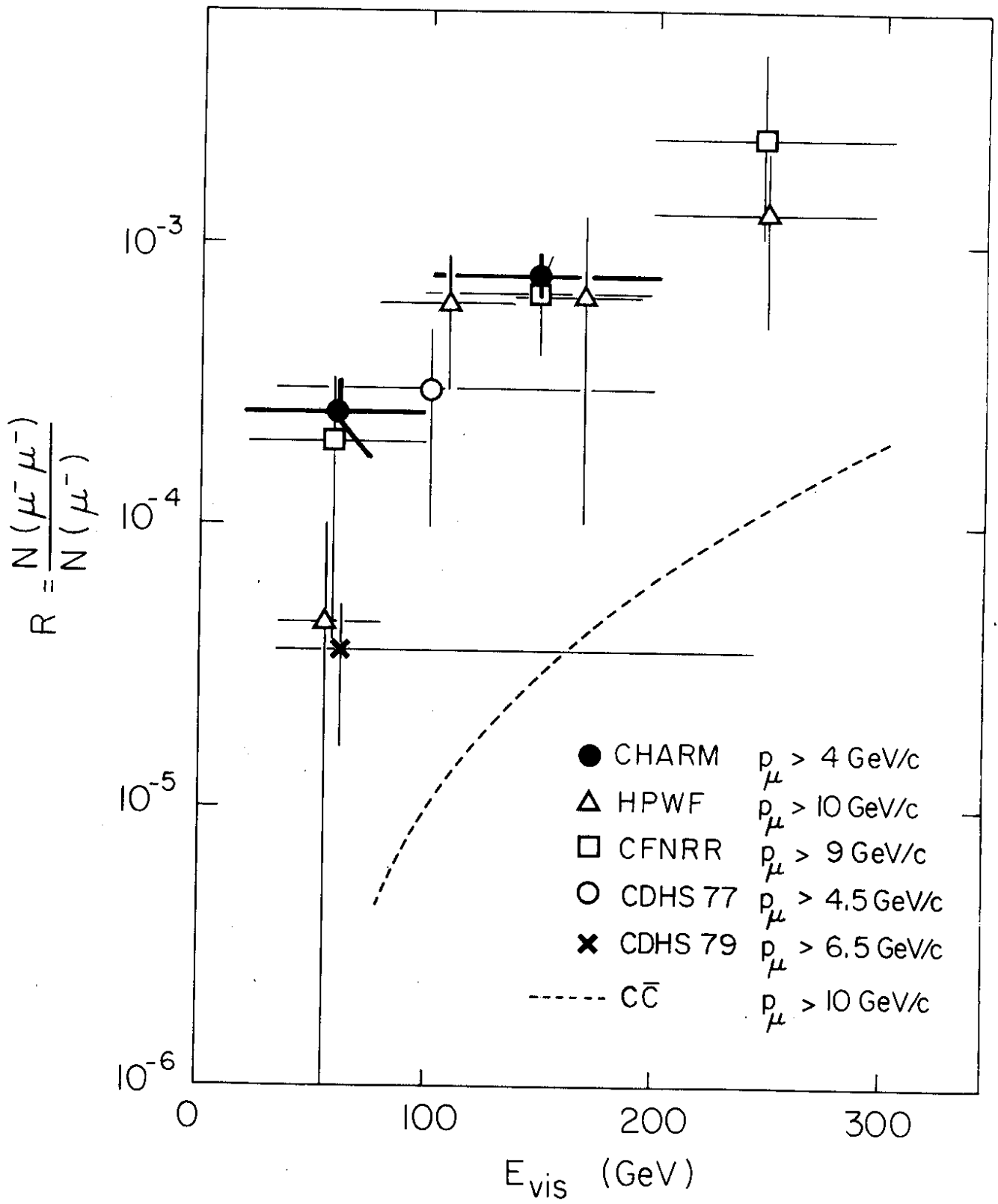


Fig. 4