EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/82-207
14 December 1982

MEASUREMENT OF THE POLARIZATION OF POSITIVE MUONS PRODUCED IN HIGH-ENERGY ANTINEUTRINO INTERACTIONS

M.Jonker and F.Udo
NIKHEF, Amsterdam, The Netherlands

J.V.Allaby, U.Amaldi, G.Barbiellini1),
A.Capone2), W.Flegel, M.Metcalf, J.Meyer3), F.L.Navarria4)
J.Panman, A.M. Wetherell and K.Winter
CERN, Geneva, Switzerland

F.W.Büsser, H. Daumann, P.D.Gall, E.Metz,
F.Niebergall, K.H.Ranitzsch and P.Stähelin
II. Institut für Experimentalphysik5),
Universität Hamburg, Hamburg, Germany

E.Grigoriev, V.Kaftanov, V.Khovansky and A.Rosanov
Institute for Theoretical and Experimental Physics, Moscow, USSR

A.Baroncelli6), B.Borgia7), C.Bosio6), F.Ferroni7), E.Longo7),
P. Monacelli7), F.de Notaristefani7), P.Pistilli7), C.Santoni6),
and V.Valente7)
Istituto Nazionale di Fisica Nucleare, Rome, Italy

(Submitted to Zeitschrift für Physik C)

---

1) On leave of absence from INFN, LN Frascati, Italy.

2) On leave of absence from Istituto di Fisica, University of Rome and INFN Sezione di Roma, Italy.

3) Now at DESY, Hamburg, Germany.

4) Visitor from the University and INFN, Bologna, Italy.

5) Supported by Bundesministerium für Forschung und Technologie, Bonn, German Federal Republic.

6) INFN Sezione Sanità and Istituto Superiore di Sanità, Rome, Italy.

7) Istituto di Fisica, University of Roma and INFN Sezione di Roma, Italy.

8) Laboratori Nazionali INFN Frascati, Italy.

ABSTRACT

The question whether scalar-type interactions contribute to weak interactions at large momentum transfer has been investigated by a measurement of the longitudinal polarization of positive muons produced in charged-current interactions of high-energy antineutrinos with iron. At an average momentum transfer $<Q^2> = 4$ GeV^2 the muon spin is found to be oriented forward with respect to the muon momentum vector, with an average polarization of 1.10 ± 0.24, consistent with positive helicity. A limit on scalar contributions of $\sigma_{s,p}/\sigma_{tot} < 7\%$ at the 95% confidence level can be deduced. A search for violation of time reversal invariance which could manifest itself by a polarization component perpendicular to the muon production plane gave a limit of $\sigma_{tv}/\sigma_{tot} < 16\%$ (95% c.l.). It is concluded that the weak leptonic charged current retains its dominant vector and axial vector structure at large momentum transfers.

INTRODUCTION

Weak charged-current interactions have been discovered and extensively studied in decay processes of nuclei and subsequently also in elementary particle decays. Theoretically these processes can be interpreted as a local interaction of four fermions resulting in an effective Lagrangian of the current-current type. In the most general case, five different possible interaction types, characterized by their Lorentz-transformation properties, have to be taken into account: scalar (S), pseudoscalar (P), vector (V), axial vector (A) and tensor (T). From the various decay experiments involving low energies and low momentum transfers, the so-called (V-A) theory was derived, implying that within the experimental errors only V- and A-contributions take part in the charged-current interaction with equal strength but opposite phase. Upper limits for S- and T-contributions$^{1)}$ relative to the V- and A- parts respectively could be deduced from β-decay experiments: $g_s/g_v = -0.001 \pm 0.006$ and $g_t/g_a = -0.0004 \pm 0.0003$. Contributions of (V+A)-terms in the amplitude have to be less than 10%$^{2)}$. The corresponding limits derived from the only purely leptonic decay process $\mu \to e\nu_e\ \nu_\mu$ are even less precise$^{3)4)}$.

With the advances in particle accelerators it became possible to test the structure of weak charged-currents at higher energies and higher momentum transfers. The improvement of neutrino beams opened the possibility to study the reaction

$$\bar{\nu}_\mu + N \to \mu^+ + X$$

i.e. the inclusive scattering of antineutrinos on nucleons with high statistics. The y-distribution $[y = E_x\ /E_\nu]$ for that process is, neglecting antiquarks, given by$^{5)}$:

$$d\sigma/dy \approx 2(g_v - g_a)^2 + 2(g_v + g_a)^2(1-y)^2$$

$$+ (|g_s|^2+|g_p|^2)y^2 + 32|g_t|^2(1-y/2)^2$$

$$+ 8\ \mathrm{Re}[g_t(g_s{}^* + g_p{}^*)]\ y(1-y/2).$$

g_v, g_a, g_s, g_p and g_t are the coupling-constants related to the various interactions. This expression shows that an increase in the y-distribution towards high y is clear evidence that S and/or P-terms are present in the interaction. The experimental data 6)7) for the inclusive antineutrino charged-current scattering on nucleons show a decreasing y-distribution. The data are consistent with a parametrization $d\sigma/dy = a+b(1-y)^2$ expected for V- and A-interactions. Assuming the absence of T-interactions a limit on S- and P-terms, manifesting themselves by a y^2-term could be derived by the CHARM Collaboration 6) and by the CDHS Collaboration 7) to be $g_{s,p}{}^2/g_{v,a}{}^2 < 0.06$ at the 95% confidence level. It should be stressed that a y^2-term could also be caused by a violation of the Callan-Gross relation 8), so that the quoted limit is not unambiguous. It has been pointed out 9), that a decreasing y-distribution can also be described by an appropriate mixture of S, P and T interactions (the so-called confusion-theorem). Measurements of the helicity of muons produced in neutrino/antineutrino interactions can resolve this ambiguity 10) as currents of the V and A-type preserve the helicity at the lepton vertex, whereas interactions of the S, P and T-type flip the helicity. Hence, positive muons from antineutrino interactions are expected to have positive helicity if the interaction is V and/or A and negative helicity if the interaction is S, P or T provided the helicity of the incident antineutrinos is positive as in the case of high-energy antineutrinos produced by pion and kaon decays, the main sources of high energy antineutrino beams 11)12). Such an experiment constitutes a very direct test of possible S,P, and T contributions to the interaction.

THE EXPERIMENTAL SCHEME

Here we report on measurements of the polarization of positive muons produced in inclusive semileptonic antineutrino-iron interactions $\bar{\nu}_\mu$ + Fe → μ^+ + X. First results[13)] of these measurements have been published previously. In a more detailed analysis based on significantly higher statistics the dependence of the polarization on the kinematical quantities x, y, and Q^2 has been studied in addition. From these measurements a limit on S- and P-contributions to the weak charged-current interaction can be given which is free from ambiguities with effects due to the violation of the Callan-Gross relation. In addition a limit for the violation of the time-reversal invariance can be obtained by searching for transverse polarization components.

The experimental arrangement has been described elsewhere[13)]. The set-up consists of two parts, the target and the polarimeter, exposed to the horn-focussed wide band antineutrino beam produced by 400 GeV protons from the CERN-SPS which has a spectrum peaked around 25 GeV. A schematic view of this set-up is shown in Fig.1.

The neutrino-detector[14)] of the CDHS collaboration served as an active target. Its instrumentation allowed the measurement of the momentum vector $\vec{p}_\mu$ of the produced positive muon and of the hadronic energy E_x of the recoiling system X and rejection of muons produced upstream and of cosmics. The toroidal field of the detector focussed the muons on their passage through up to 14 m of iron towards the CHARM-detector[15)], used in this case as a polarimeter for the muons. Marble (CaCO3) was chosen as target material in order to minimize depolarization effects. The surrounding iron frame of the polarimeter was magnetized such that a magnetic field of 58 G transverse to the beam direction was produced inside the polarimeter. The field was measured and found to be homogeneous to within 3%. Approximately 3% of the muons produced in the target stopped inside the polarimeter. The projection of the spin of a stopped muon onto a plane perpendicular to the plates of the polarimeter was forced by the magnetic field to precess in this plane with a period of 1.3 μs.

Positrons from muon-decay were detected in a scintillator plane either backward (upstream) or forward (downstream) with respect to the marble plate in which the muon had stopped. In the muon decay $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ high energy positrons are emitted preferentially in the direction of the muon spin. It is therefore expected that a time-dependent forward-backward asymmetry of positrons should be observed. The energy deposited by a positron in the scintillators and the time which elapsed between the stopping of the muon and the appearance of a positron, were recorded. The arrangement of the detector elements13)15) did not allow any distinction between a muon stopped in a marble plate or in the preceding scintillator plane. Thus decay positrons from muons which stopped in one of the scintillators were always assigned to backward decays.

The method of spin precession is insensitive to systematic forward-backward asymmetries of the apparatus and allows the determination of the degree of longitudinal polarization from the amplitude of the time dependent relative backward-forward positron yield. The polarimeter was triggered (early trigger) by a combination of scintillators corresponding to a track of a stopping muon. When such a trigger occurred a time-gate of 6 μsec was opened, during which a scintillator pulse (late trigger) was accepted as a decay positron candidate. The zero point of the muon decay time measurement was determined for all stopping planes with an error of ±0.015 μs. The linearity and the homogeneity of the scale of the time measurement was checked before each running period.

THE DATA ANALYSIS

During an antineutrino beam exposure corresponding to $2.86 \cdot 10^{18}$ protons on target, 195,473 events have been recorded, triggered by a total energy release in the target calorimeter of at least 7 GeV, in coincidence with the signal for a track penetrating into the polarimeter and stopping there.

The following selection criteria were applied:

I. In the target calorimeter

1. The interaction vertex had to lie within a fiducial volume which covers a circular area of 175 cm radius perpendicular to the beam axis and extends longitudinally from the third scintillator plane to the end of module 13 (the total target consists of 19 modules[14)]). To exclude upstream muons a veto signal from an anticounter in front of the target was used.

2. A muon of positive charge was required.

3. The event had to pass successfully the analysis chain of the target detector.

II. In the polarimeter

1. The stopping-point of the muon was required to be located longitudinally in the range of the target plates 9 to 74 out of a total of 78, and within a square lateral area covering the region from -135 to +135 cm around the beam axis.

2. The decay positron had to be recorded within the time window $0.94 < t < 4.89$ μsec after the muon came to rest.

3. The lateral distance between the stopping point of the muon and the centre of the scintillator in which the decay positron had

been seen, was limited to ± 30 cm. The efficiency of this cut for positrons from muon decay is 96%.

Tracks caused by muons entering the target from the front and the sides were excluded. After these cuts 17,484 events were left, out of which 6,629 were classified as "quasielastics", having an energy of the final hadronic system of less than 3 GeV.

There are two kinds of background. One is correlated with the stopping muon signal coming from a reflection of the muon signal at the phototubes and from after-pulsing of the multipliers. The other is uncorrelated with the stopping muon and caused by steep cosmic muons and random noise. The latter background has a flat distribution within the time gate which is opened by the early trigger. The cut made in the distribution of the lateral distance between the stopping point of the muon and the point where the decay positron had been seen, reduced that background to about (0.6 ± 1.1)%. In the correlated background a late trigger may be simulated only in those scintillators, which have been crossed by a muon. Thus this background contributes only to the backward decays and therefore a forward-backward asymmetry will be simulated. The background due to reflections can be eliminated by a cut in the time distribution ($t \geq 0.94$ μsec). The after-pulsing of the multipliers gives a flat background in the time distribution. After these cuts a total background of (2.0 ± 2.0)% is left with a backward-forward asymmetry of 4:1. The detection efficiency for positrons from muon decay is after all corrections (17.3 ± 0.4)%.

POLARIZATION RESULTS

From the observed time distribution of the decay positrons a muon mean lifetime of 2.25 ± 0.04 μsec has been derived in good agreement with that expected for positive muons. Figure 2 shows the decay time distribution of the muons. The observed time dependence of the backward-forward asymmetry

$$R(t) = [N^b(t)-N^f(t)]/[N^b(t) + N^f(t)]$$

is shown in Fig.3. It can be parametrized as $R(t) = R_0 \cos(\omega t + \phi) + R_1$. The magnetic field of 58G induced a muon-spin precession frequency of $\omega = 4.92$ MHz. The phase ϕ is expected to be zero for negative helicity and $-\pi$ for positive helicity of the muon. The oscillation amplitude R_0 is proportional to the magnitude of the longitudinal polarization P with the polarimeter analyzing power α as proportionality constant ($R_0 = \alpha \cdot P$). Positrons from muons which stop and decay in a scintillator rather than a marble plate produce the offset R_1 and also diminish the oscillation amplitude R_0. The oscillation amplitude R_0 can be directly related to the difference of amplitudes due to helicity conserving terms, $R_{v,a}$ and helicity flipping terms $R_{s,p,t}$ by substituting their respective phase angles $\phi = -\pi$ and 0,

$$R(t) = (R_{v,a}-R_{s,p,t})\cos(\omega t-\pi) + R_1,$$

$$R_0(\phi=-\pi) = R_{v,a}-R_{s,p,t}.$$

The value of the analyzing power α was determined by a Monte-Carlo simulation program, where the reaction $\bar{\nu}_\mu + \mathrm{Fe} \rightarrow \mu^+ + X$ was simulated in detail using the known wide-band beam spectrum and the measured cross section⁶⁾ in iron. The positive muons have been tracked through the remaining part of the target and the polarimeter until they came to rest; the magnetic field in the target, the energy losses by ionisation and bremsstrahlung, and the multiple scattering were taken into account. At the stopping point the muon-decay was simulated according to the measured distributions. The passage of the decay positron through matter was treated by a Monte Carlo-program (EGS¹⁶⁾), where energy loss by ionization, radiation, pair production, Compton scattering and multiple scattering have been taken into account. Figure 4 shows the spectra of energy loss by the positrons in the scintillators for forward (a) and backward (b) decays of the stopping muon derived from the data and from the Monte-Carlo simulation program.

Table 1 gives a comparison of the parameters R_0, R_1, and ϕ obtained by a fit to the data and their values obtained by the Monte Carlo simulation assuming a helicity of the positive muon of +1. The remaining asymmetric background has been taken into account. Varying the threshold of positron detection in the data from 2 to 6 MeV increases R_0 by 0.003, negligible compared to the statistical error of 0.010.

Table 1

	Data	M.C. (P=+1 no depolarization)
R_0	0.116 ± 0.010	0.148 ± 0.004
ϕ	-3.02 ± 0.08	-3.12 ± 0.03
R_1	0.364 ± 0.007	0.364 ± 0.003

The measured phase is an absolute determination, it is consistent with the value of $-\pi$ and shows that the positive muons have positive helicity. This result indicates that S, P, or T terms do not dominate the interaction. In a second fit to the data the phase was fixed at $\phi = -\pi$ and R_0 is then the difference of the oscillation amplitudes of helicity-conserving (V,A) and helicity-changing (S,P,T) interactions. The result is the same as that shown in Table 1 and agrees with V,A interaction dominance.

The comparison of the parameters determined from the experimental data with those of the MC-calculation results in an absolute value for the longitudinal μ^+-polarization of P = +0.78 ± 0.07(stat). In order to interpret this result, depolarization effects have to be taken into account. The muon may suffer some depolarization in the stopping material, resulting from Mott-scattering, spin-spin interaction, bremsstrahlung or production of muonium. The first effect was estimated to be less than 1%[17)18)19)]. The depolarization by spin-spin interactions can be neglected since marble is composed of nuclei with zero spin. For the depolarization by bremsstrahlung, calculations for a similar problem in synchrotron radiation[20)21)] can be used. The probability that the lepton flips the spin by radiation turned out to be orders of magnitude smaller than the case where the lepton does not flip the spin. Depolarization by muonium production has been studied by a comparative measurement of the polarization analysing power of the marble structure described above and of an identical polarimeter structure using carbon plates as stopping material. This experimental study was done using polarized muons from decays in flight of 140 MeV/c pions at the CERN synchrocyclotron (SC). The relative polarization analysing power of the marble structure normalized to that of the carbon structure was found to be 0.96 ± 0.08. Since carbon is known to be non-depolarizing[22)] (residual polarization is 100 ± 6%) it can be concluded that the residual polarization of muons stopped in marble is (96 ± 10%). The quoted error is part of a systematic error. Another part comes from the uncertainty of the energy loss spectra of the positrons in the scintillators resulting from threshold effects or systematic error in tracking the positrons. These effects were estimated to be 7%, the total systematic error to 12%. Correcting the above quoted value of P one gets an absolute value for the polarization of $P = +0.82 \pm 0.07$ (stat) ± 0.12 (syst). From this value upper limits of $\sigma_{s,p,t}/\sigma_{tot} < 13\%$ at the 68% confidence level and $\sigma_{s,p,t}/\sigma_{tot} < 20\%$ at the 95% confidence level can be set on S, P or T contributions to charged current interactions at an average momentum transfer of $\langle Q^2 \rangle = 4.0$ (GeV/c)^2. Table 2 shows the average values of some kinematical quantities of the reaction $\bar{\nu}_\mu + \mathrm{Fe} \rightarrow \mu^+ + \mathrm{hadrons}$.

Table 2

$\langle p_h \rangle = 16.1 \pm 0.04$ GeV/c
$\langle E_h \rangle = 14.1 \pm 0.11$ GeV
$\langle E_{tot} \rangle = 30.3 \pm 0.12$ GeV
$\langle y \rangle = 0.404 \pm 0.001$
$\langle x \rangle = 0.189 \pm 0.002$
$\langle Q^2 \rangle = 4.0 \pm 0.04$ (GeV/c)^2

Since the target was heavily instrumented, the muon momentum $\vec{p}_\mu$ and the hadronic energy E_x could be measured, and the quantities x, y and Q^2 determined. Figs. 5a,b,c show the measured oscillation amplitude R_0 as a function of the kinematical quantities y, x and Q^2, respectively. No obvious dependence on these quantities can be seen. The "quasielastic" events were included in the y and Q^2 dependence of R_0 contributing mainly to the first bin in both cases.

From the y-dependence of R_0 an increased sensitivity to S and P contributions is obtained assuming contributions of T to be negligible. This is illustrated in Fig. 6, which shows the expected polarization P as a function of S and P contributions for various bins in y. Using the events for $y < 0.2$ as normalisation (here the possible S and P contributions are negligible, since they are proportional to y^2), we find a polarization of $P = 1.10 \pm 0.24$ corresponding to an upper limit of $\sigma_{s,p}/\sigma_{tot} < 7\%$ at the 95% c.l. Here only the events for $y > 0.5$ were used (in that region S and P contributions would dominate V and A interactions). The y-dependence of the efficiency was taken into account. Contributions due to a violation of the Callan-Gross relation are excluded by this method.

SEARCH FOR VIOLATION OF TIME REVERSAL INVARIANCE

The same data provide a limit for the violation of time reversal invariance. Violation of time reversal invariance would manifest itself by the observation of a polarization component perpendicular to the μ^+-production plane, i.e. by the presence of a $\vec{\sigma}_\mu \cdot (\vec{p}_\mu \times \vec{p}_\nu)$ term. In the polarimeter only a polarization component in the horizontal plane (perpendicular to the magnetic field) could be measured, hence the experiment is sensitive only to a polarization component out of the vertical production plane. A violation of time reversal invariance would influence the phase ϕ of the backward-forward asymmetry R(t) (deviation from $\phi = -\pi$). Two samples of events were analysed determined by a cut in the azimuthal muon production angle Φ, (Fig. 7) which covers the range -180° to +180°. One sample, ϕ_1, is taken for the interval $|\Phi| \leq 60°$ and the other, ϕ_2, for the interval $|\Phi| \geq 120°$. These samples are composed of T-invariance conserving (TC) and of T-invariance violating (TV) contributions,

$$\sigma_{tot} \cdot \phi_1 = \sigma_{tc} \cdot \phi_{tc} - \sigma_{tv}\, \phi_{tv}$$

$$\sigma_{tot} \cdot \phi_2 = \sigma_{tc} \cdot \phi_{tc} + \sigma_{tv}\, \phi_{tv}$$

with phases $\phi_{tc} = \pi$ and $\phi_{tv} = \pm \pi/2$. The values for the parameters R_0, ϕ, and R_1 of the two samples are given in table 3.

Table 3

	field polarity	R_0	ϕ	R_1
all data		0.116 ± 0.010	-3.02 ± 0.08	0.364 ± 0.007
$\|\Phi\| < 60°$ (upper hemisphere)	+	0.128 ± 0.023	-2.92 ± 0.18	0.378 ± 0.016
$\|\Phi\| > 120°$ (lower hemisphere)	+	0.133 ± 0.026	-2.90 ± 0.18	0.399 ± 0.018
$\|\Phi\| < 60°$ (upper hemisphere)	-	0.136 ± 0.023	-3.15 ± 0.17	0.352 ± 0.017
$\|\Phi\| < 120°$ (lower hemisphere)	-	0.105 ± 0.027	-3.35 ± 0.25	0.353 ± 0.018

Since a T-violating term proportional to $\vec{\sigma}_\mu \cdot (\vec{p}_\mu \times \vec{p}_\nu)$ has a different sign in the two different Φ-regions an upper limit for the cross section σ_{tv}, violating the time reversal invariance, relative to the total cross-section, σ_{tot}, can be derived from the difference in the oscillation phases $\phi_1-\phi_2$ for the two Φ-samples. That was done for the two magnetic settings separately, with the result

$$\sigma_{tv}/\sigma_{tot} = |\phi_1-\phi_2|/\pi = (3.5 \pm 6.3) \cdot 10^{-2}.$$

Correcting for the average value of Φ, $\langle\cos\Phi\rangle = 0.8$, we find a limit for time-invariance violating contributions of

$$\sigma_{tv} / \sigma_{tot} \leq 16\%$$

at the 95% confidence level for $\langle Q^2\rangle = 4$ GeV^2. The corresponding limit[23)] from β-decay of polarized neutrons ($Q^2 \approx 10^{-6}$ GeV^2) is 0.1%.

CONCLUSIONS

The new measurement reported here of the polarization of positive muons produced in inclusive semileptonic reactions induced by antineutrinos on iron is based on large statistics and on kinematically reconstructed events. The muon spin is found to be oriented forward with respect to the muon momentum vector with an average polarization of 0.82 ± 0.07(stat) ± 0.12(syst) at a mean momentum transfer of $\langle Q^2\rangle = 4$ GeV^2 corresponding to an upper limit of $\sigma_{s,p,t}/\sigma_{v,a} < 20\%$ at the 95% confidence level. No dependence of the polarization on the kinematical quantities x,y and Q^2 was found. A decrease of the polarization and, hence, of the asymmetry for $y > 0.5$ would be clear evidence for scalar contributions to the reaction. Comparison of the asymmetry for $y < 0.2$ where S and P terms cannot induce helicity flip, and $y > 0.5$ where they would dominate over V,A terms gives an upper limit of $\sigma_{s,p}/\sigma_{tot} < 7\%$ (95% c.l.). Contributions due to a violation of the Callan-Gross relation can be excluded by this measurement.

A search for a polarization component perpendicular to the muon production plane gives the first limit on time reversal violation (tv) at $\langle Q^2 \rangle \approx 4$ GeV^2, $\sigma_{tv}/\sigma_{tot} < 16\%$ at the 95% confidence level.

It is concluded that the weak leptonic charged current retains its dominant vector and axial-vector and time-reversal invariant structure at the large momentum transfers accessible in high-energy neutrino interactions.

ACKNOWLEDGEMENTS

This experiment could be performed thanks to the help of the CERN-Dortmund-Heidelberg-Saclay Collaboration which built the massive neutrino detector, used as target in the present experiment, and operated it during data taking. They also assisted us in the kinematical reconstruction of the events. We are very grateful for this essential contribution.

We would like to thank most sincerely our many technical collaborators and the members of the SPS staff for the operation of the accelerator.

REFERENCES

1. H. Paul, Nucl. Phys. A154, (1970) 160

2. F.W. Koks and J. van Klinken, Nucl. Phys. A272, (1976) 64

3. S.E. Derenzo, Phys. Rev. 181 (1969) 1854

4. M. Strovink, LBL Report 12275 (1980)

5. R.L. Kingsley et al., Phys. Rev. D10, (1974) 2216

6. M. Jonker et al., Phys. Lett. 109B, (1982) 133

7. J.G.H. de Groot et al., Z. Phys. C1 (1979) 143

8. C.C.Callan and D.J.Gross, Phys. Rev. Lett. 22, (1969) 156

9. B. Kayser et al., Phys. Lett. 52B (1974) 385

10. T.P. Cheng and Wu-Ki Tung, Phys. Rev. D3, (1971) 733

11. C.A. Coombes et al., Phys. Rev. 108, (1957) 1348

12. G. Backenstoss et al., Phys. Rev. Lett. 6, (1961) 415

13. M. Jonker et al., Phys. Lett. 86B, (1979) 229

14. M. Holder et al., Nucl. Instrum. Meth. 148, (1978) 235

15. A.N. Diddens et al., Nucl. Instrum. Meth. 178, (1980) 27

16. R.L. Ford, W.R. Nelson, SLAC Report 210/UC32 (1978)

17. G. Wentzel, Phys. Rev. 75, (1949) 1810

18. J.W. Motz, H. Olsen and H.W. Koch, Rev. Mod. Phys. 36, (1964) 881

19. G.W. Ford and C.J. Mullin, Phys. Rev. 108, (1957) 477

20. J.D. Jackson, Rev. Mod. Phys. 48, (1976) 417

21. V.N. Baier, Sov. Phys. Uspekhi 14, (1972) 695

22. R.A. Swanson, Phys. Rev. 112, (1958) 580

23. R.I. Steinberg, P. Liand, B. Vignon and V.W. Hughes, Phys. Rev. Lett. 33, (1974) 41

FIGURE CAPTIONS

Fig. 1 Layout of the polarization experiment, showing the CDHS neutrino detector used as a target and the CHARM fine-grain calorimeter used as a polarimeter

Fig. 2 Observed decay time distribution of muons with positive charge

Fig. 3 Observed time dependence of the relative backward-forward positron oscillation amplitude, $R_0(t) = [N(B)-N(F)]/[N(B)+N(F)] = R_0\cos(\omega t+\phi) + R_1$

Fig. 4 Energy loss distribution of decay positrons in the scintillators for (a) forward and (b) backward decays of the stopping muons, from the experimental data and from a Monte Carlo simulation. The distributions are normalized to the same area

Fig. 5 Measured oscillation amplitude R_0

a) as a function of the inelasticity $y = E_x/E_\nu$;

b) as a function of $x = Q^2/2ME_x$

c) as a function of Q^2

Fig. 6 Expected polarization for different regions of y as a function of S and P-contributions, illustrating the sensitivity of the experiment.

Fig. 7 Schematic sketch of the event selection in the reaction plane for searching time-reversal invariance violating contributions

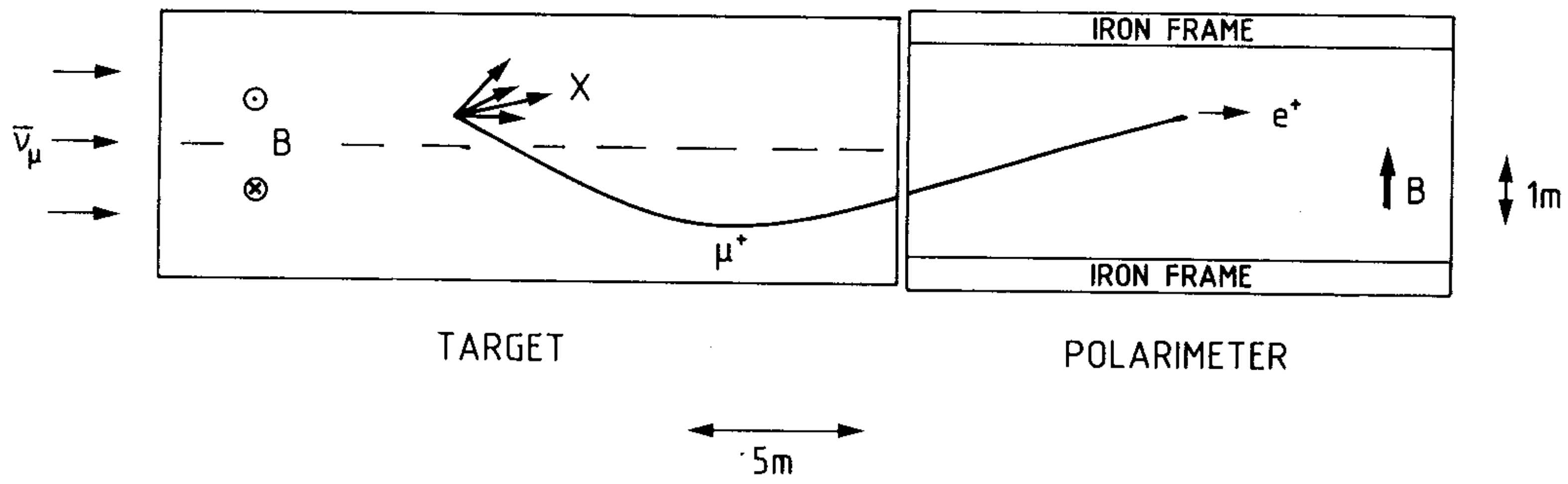
IRON FRAME
X
$\bar{\nu}_\mu$
⊙
B
⊗
e^+
B
1m
μ^+
IRON FRAME
TARGET
POLARIMETER
5m

Fig. 1

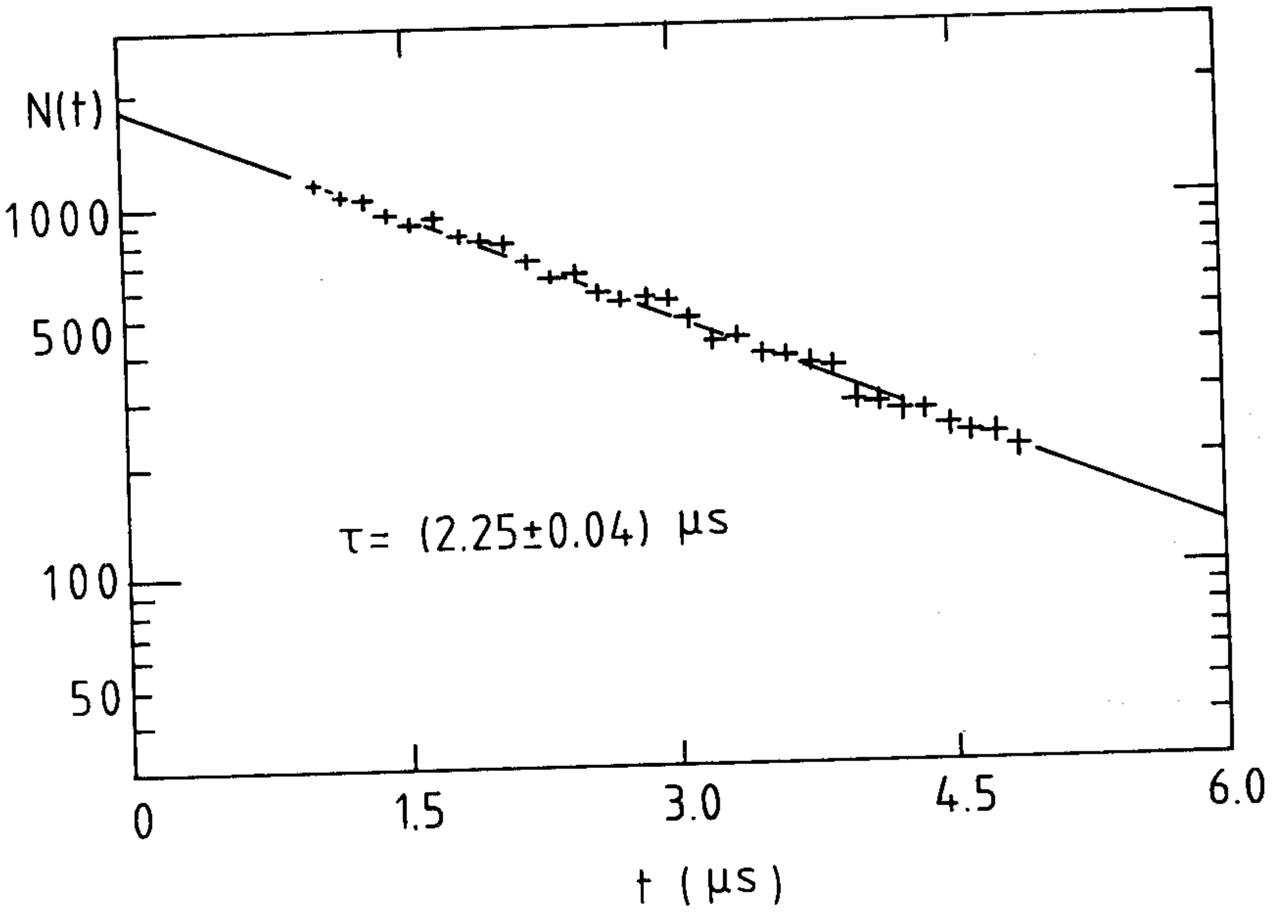

Fig. 2

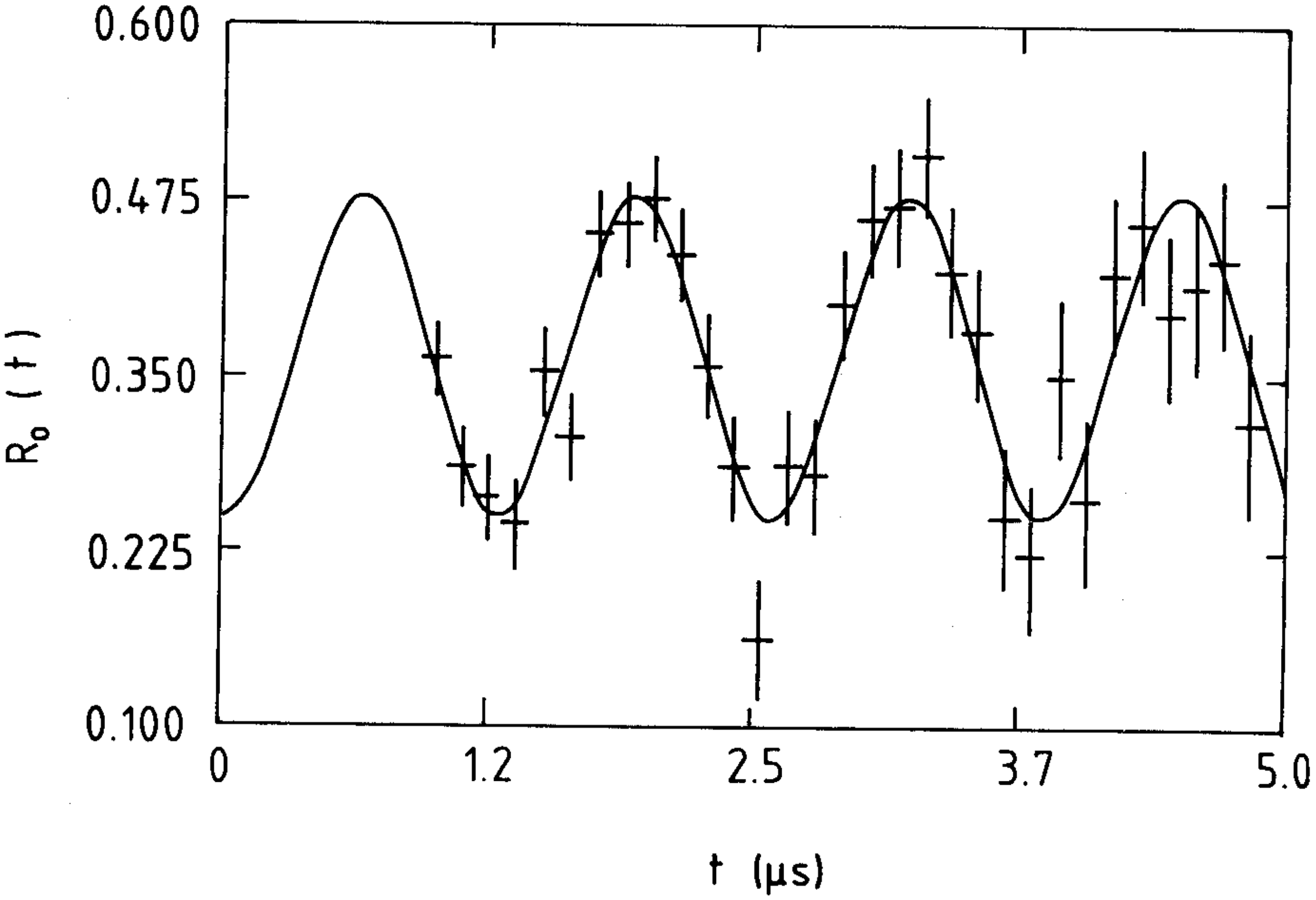

Fig. 3

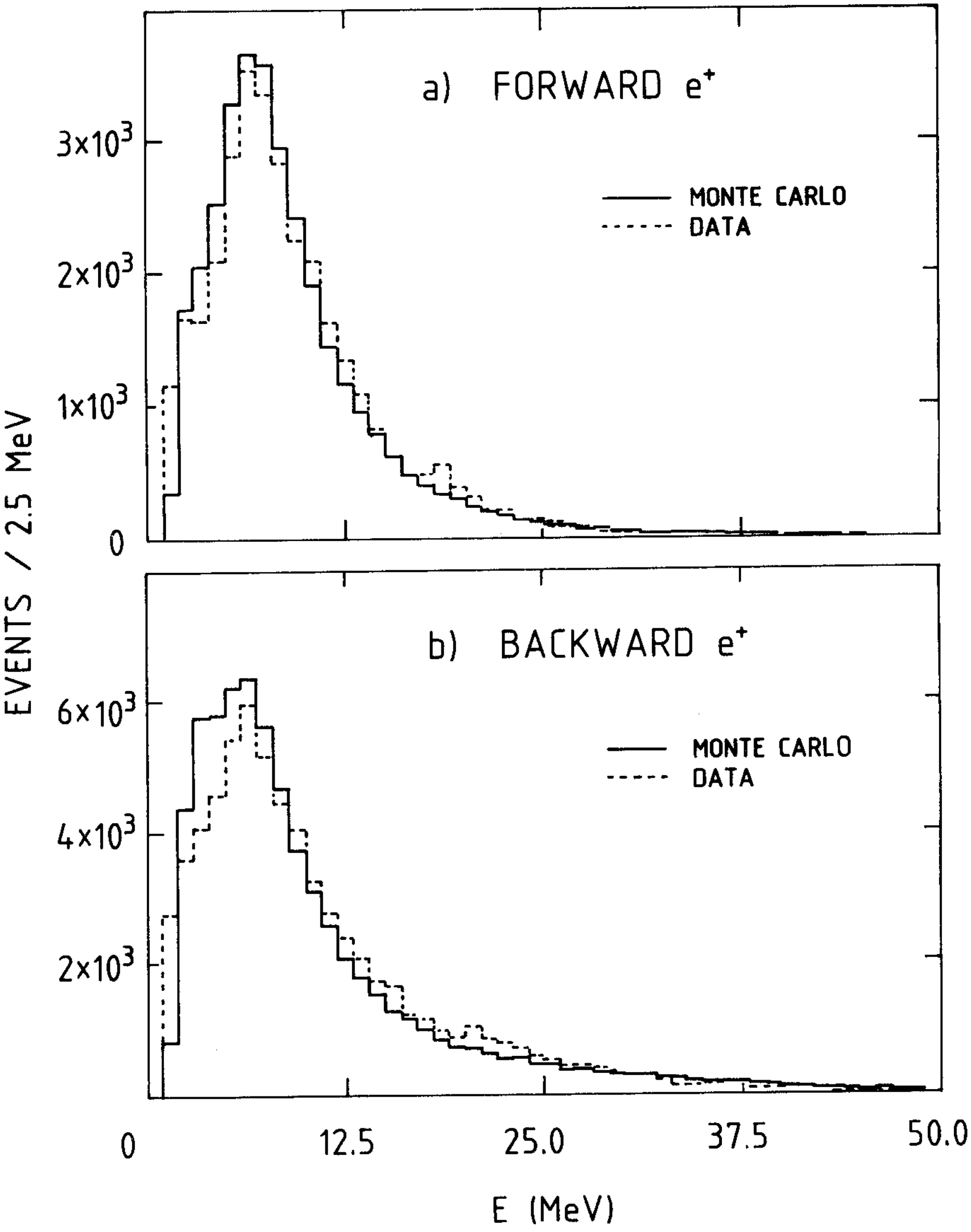
a) FORWARD e^+
MONTE CARLO
DATA
b) BACKWARD e^+
MONTE CARLO
DATA
EVENTS / 2.5 MeV
0
1×10^3
2×10^3
3×10^3
2×10^3
4×10^3
6×10^3
0
12.5
25.0
37.5
50.0
E (MeV)

Fig. 4

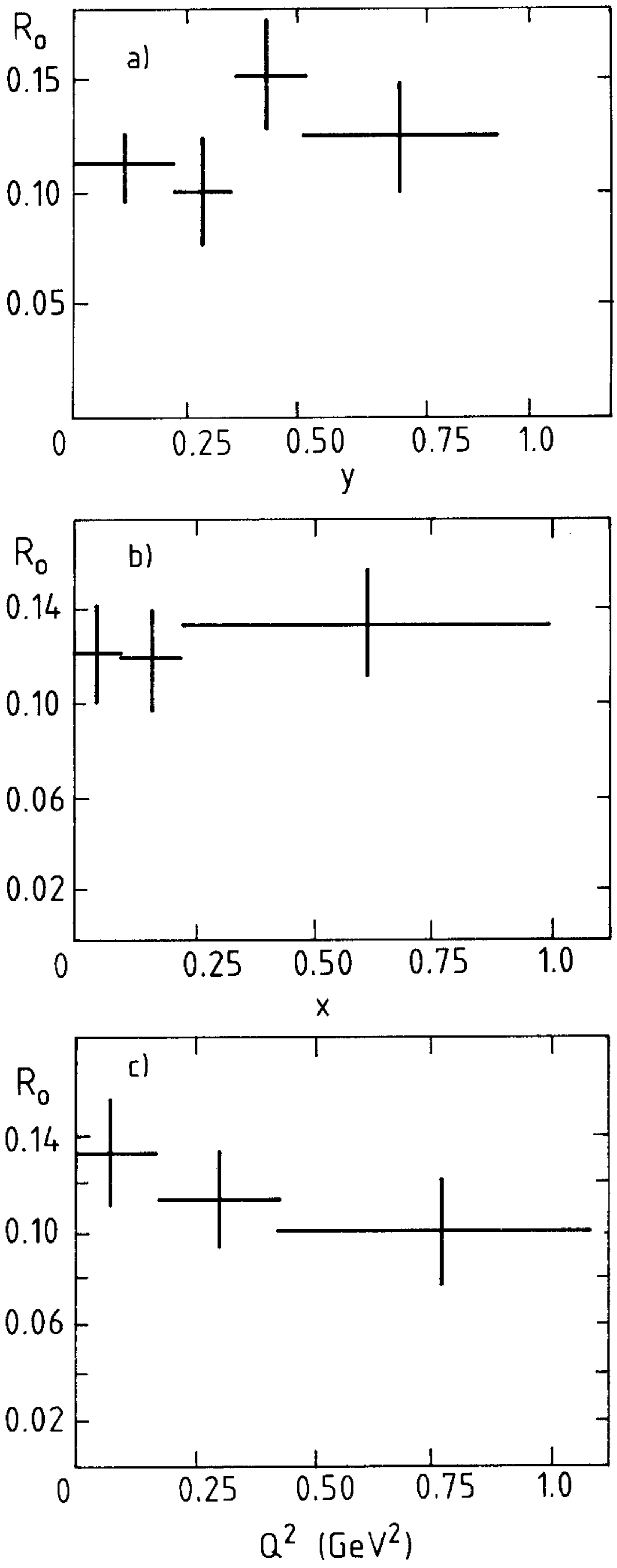
a)
R_o
0.15
0.10
0.05
0
0.25
0.50
0.75
1.0
y
b)
R_o
0.14
0.10
0.06
0.02
0
0.25
0.50
0.75
1.0
x
c)
R_o
0.14
0.10
0.06
0.02
0
0.25
0.50
0.75
1.0
Q^2 (GeV^2)

Fig. 5

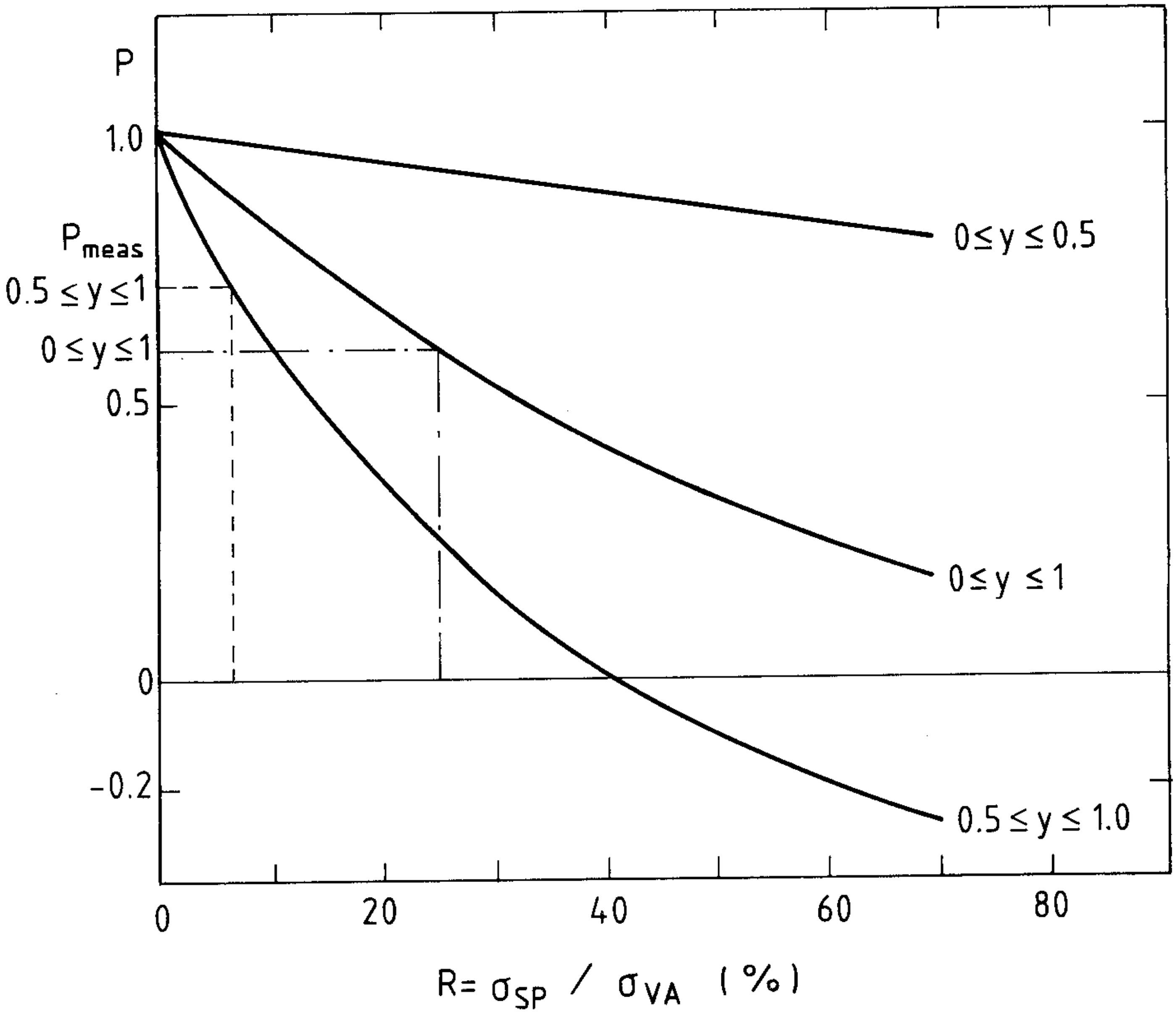
P
1.0
P_{meas}
$0.5 \leq y \leq 1$
$0 \leq y \leq 1$
0.5
0
-0.2
$0 \leq y \leq 0.5$
$0 \leq y \leq 1$
$0.5 \leq y \leq 1.0$
0
20
40
60
80
$R = \sigma_{SP} / \sigma_{VA}$ (%)

Fig. 6

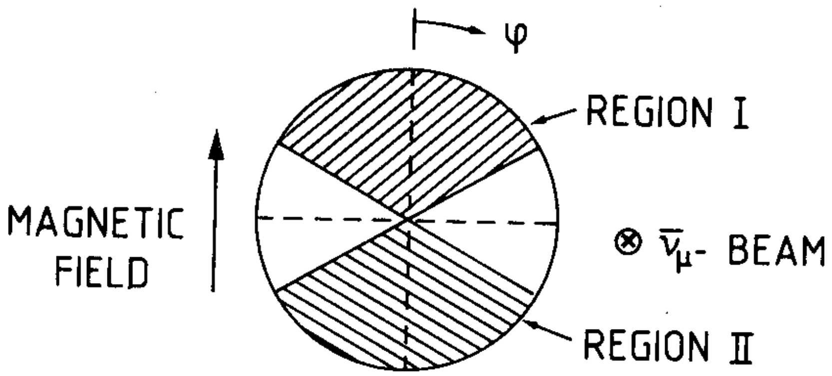

Fig. 7