ELECTROWEAK ASYMMETRY IN DEEP INELASTIC MUON- NUCLEON SCATTERING

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At the CERN SPS we have measured a deep inelastic $\mu\pm$ cross section asymmetry at momentum transfers Q^2 ranging from 15 to 180 GeV^2. The result is in quantitative agreement with the WS/GIM standard electroweak model and allows to determine the muon neutral current couplings.

1. Introduction. Since the discovery of weak neutral currents in 1973 [1], several neutrino and electron scattering experiments have studied their structure in detail confirming the predictions of the WS/GIM model [2]. Still, it is considered important

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to study the neutral currents in new kinematical regions and different reaction channels [3].

In the deep inelastic scattering of longitudinally polarized muons on nuclear targets

$$\mu^{\pm}N \rightarrow \mu^{\pm}X \tag{1}$$

the weak neutral current can be studied through its interference with the electromagnetic current [4]. The cross section for reaction (1), $\sigma^{\pm}(\lambda)$, depends on the charge and the polarization λ of the incoming muon.

At the CERN SPS we have measured the cross section asymmetry

$$B = \frac{\sigma^{+}(-|\lambda|) - \sigma^{-}(+|\lambda|)}{\sigma^{+}(-|\lambda|) + \sigma^{-}(+|\lambda|)}, \tag{2}$$

scattering muons of 120 and 200 GeV incoming energy on an isoscalar carbon target. The charge and polarization of the beam were changed by reversing the field direction of all beam magnets. Simultaneously, the field of the detector magnet was reversed to ensure equal acceptance for the scattered muons.

Taking into account the one-photon and Z^0 boson exchange to first order, the asymmetry B is equal to

$$B = -\kappa(a_{\mu} - \lambda v_{\mu})A_0 g(y)Q^2. \tag{3}$$

Here $\kappa Q^2 = Q^2 G/(\sqrt{2}\cdot 2\pi\alpha) = 1.79 \times 10^{-4}\, Q^2\ \mathrm{GeV}^{-2}$ determines the magnitude of B for a given momentum transfer Q^2; $v_{\mu}(a_{\mu})$ are the vector (axial-vector) couplings of the muon to the Z^0 and $g(y) = [1-(1-y)^2]/[1+(1-y)^2]$, y being the relative energy transfer. A_0 is a ratio of structure functions which in the valence quark approximation reduces to a combination of axial-vector quark couplings, $A_0 = \frac{6}{5}(a_{\mathrm{d}} - 2a_{\mathrm{u}})$ [4]. In the WS/GIM model $A_0 = -1.8$, $a_{\mu} = -0.5$, and $v_{\mu} = -0.5 + 2\sin^2\theta_{\mathrm{w}}$ which is nearly zero for the standard value of $\sin^2\theta_{\mathrm{w}} = 0.23$. Thus the asymmetry B is expected to be almost independent of the polarization and, unlike the asymmetry measured at SLAC [5], essentially parity conserving. The charge asymmetry is affected by higher order electromagnetic contributions. They compensate part of the electroweak effect [6] and are predominantly due to interference between one- and two-photon exchange and between lepton and hadron bremsstrahlung.

2. Apparatus and data taking. The apparatus used in this experiment is shown in fig. 1 and has been extensively described elsewhere [7]. Its good acceptance for deep inelastic scattering with large Q^2, its azimuthal symmetry which minimizes the effect of variations of beam position and direction, and the high luminosity achievable with the 40 m long carbon target make it particularly well suited for the measurement of a small asymmetry. The spectrometer consists of ten 5 m long iron toroids, magnetized to saturation, which surround the target. Keeping the magnet always on the same hysteresis loop by computer control of the excitation current, the absolute value of the field after a polarity change is reproduced with a relative precision of 2×10^{-4}. The target and iron absorb the hadronic shower close to the interaction point and the surviving scattered muon is focused towards the axis. The toroids are instrumented with twenty planes of trigger counters, which are segmented into rings to permit a Q^2 dependent trigger,

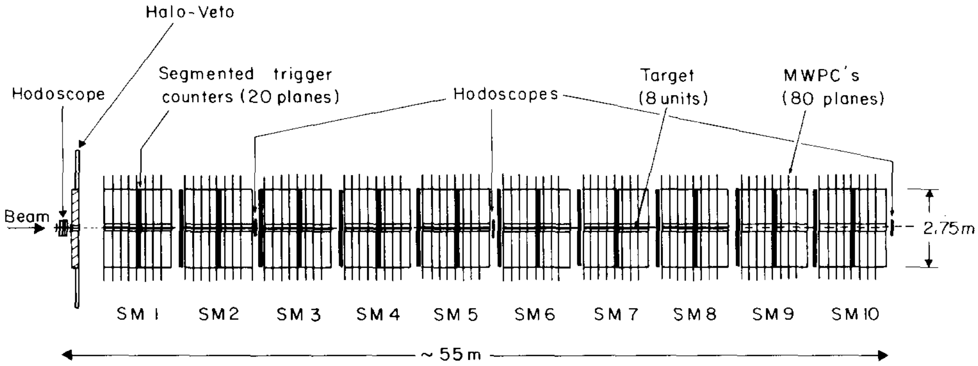

Fig. 1. Schematic layout of the experimental set-up.

and with eighty planes of multiwire proportional chambers (MWPC). Four hodoscopes along the spectrometer axis detect the incoming muons and measure their trajectories. A wall of counters in front of the spectrometer provides a veto against the beam halo.

The CERN muon beam [8] is strongly polarized in its normal operating mode where forward decay muons are selected: a Monte Carlo simulation of the beam gives $|\lambda| = 0.81 \pm 0.04$ at 200 GeV and $|\lambda| = 0.66 \pm 0.05$ at 120 GeV. The calculation for 200 GeV has been checked measuring the energy spectrum of electrons from beam muon decays [9].

The energy of each muon is measured with an accuracy of $\pm 0.5\%$ by a set of hodoscopes around one of the bending magnets of the beam. The bending power of the magnet was monitored with Hall probes, allowing a relative energy calibration of positive to negative beams with a precision of 6×10^{-4} at 200 GeV and 13×10^{-4} at 120 GeV.

The trigger required 4 consecutive trigger planes (trackes longer than ≈ 10 m) in coincidence with a beam · halo signal. The data were taken in eight periods of twelve days each; five were used for the measurement at 200 GeV with a $Q^2 > 30$ GeV^2 trigger, two periods for 120 GeV with $Q^2 > 20$ GeV^2 and one for 120 GeV with $Q^2 > 12$ GeV^2. The beam charge was reversed twice per data taking period and the intensity adjusted to about 2×10^7 μ/spill.

3. Data analysis. The total data sample was checked for stable and proper functioning of all detector components on a run-by-run basis, one run comprising about 5000 deep inelastic events. About 10% of the runs were excluded from the analysis because of hardware malfunctioning or beam instabilities. After geometrical reconstruction and kinematical fitting of tracks, rejection of background from halo feed-through and accidental triggers was based on geometrical cuts and on the requirement that tracks are geometrically consistent with the trigger pattern recorded from the scintillation counters. Events classified ambiguous by the selection program were visually inspected and about half of them, corresponding to less than 3% of all deep inelastic events, were found to be good. Including these events in the analysis does not affect the result appreciably; the effect of residual background in the accepted data sample is accounted for in the systematic errors.

Kinematical cuts were applied to exclude regions where the spectrometer acceptance varies rapidly or where radiative corrections to the deep inelastic cross section exceed 10%. These cuts, together with the number of surviving events, are summarised in table 1. The data were corrected for small differences in beam energy and for systematic differences in the efficiencies of MWPC's and trigger counters. Exploiting the redundancy of detectors in the apparatus, all efficiencies can be calculated reliably from the data themselves. The asymmetry from such effects is mostly due to the trigger counters and amounts in total to $\approx 10\%$ of the interference effect. It was evaluated for each data taking period separately and subtracted from the measured asymmetry.

The measured event rates were converted to cross sections using the muon flux counted in the beam defining hodoscope. Since care was exercised to take μ^+ and μ^- data at equal beam intensities, systematic errors in corrections for deadtime losses etc. almost cancel in the asymmetry calculation. At present, we estimate a systematic uncertainty of the relative normalisation of 4×10^{-3}.

Finally, asymmetries from all running periods were combined and corrected for higher order electromag-

Table 1
Definition of kinematic regions for the asymmetry measurements at 120 GeV (both trigger conditions) and at 200 GeV with the resulting event numbers.

Beam energy (GeV)	Q^2 range (GeV^2)	x range	y range	μ^+ events (10^3)	μ^- events (10^3)
120	15– 60	0.14–0.80	0.20–0.80	360	370
120	25–100	0.30–0.80	0.20–0.80	310	300
200	40–180	0.20–0.80	0.20–0.85	730	920

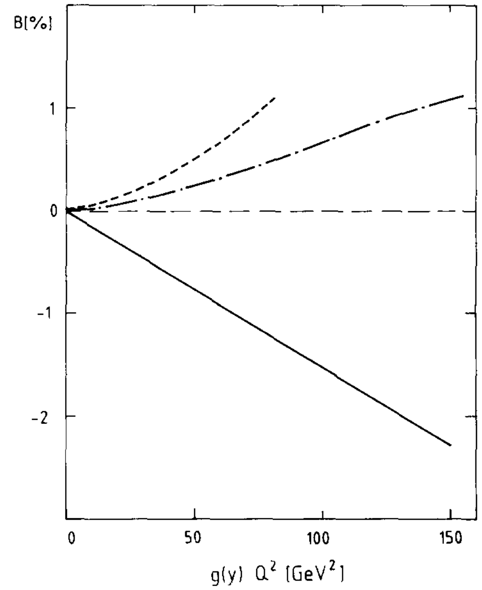

Fig. 2. The B asymmetry from $\gamma - Z^0$ interference to first order, calculated for a polarization $\lambda = 0.81$ and $\sin^2\theta_W = 0.23$ (solid line), and the asymmetry expected from higher order electromagnetic processes at beam energies of 120 GeV (dashed line) and 200 GeV (dashed–dotted line).

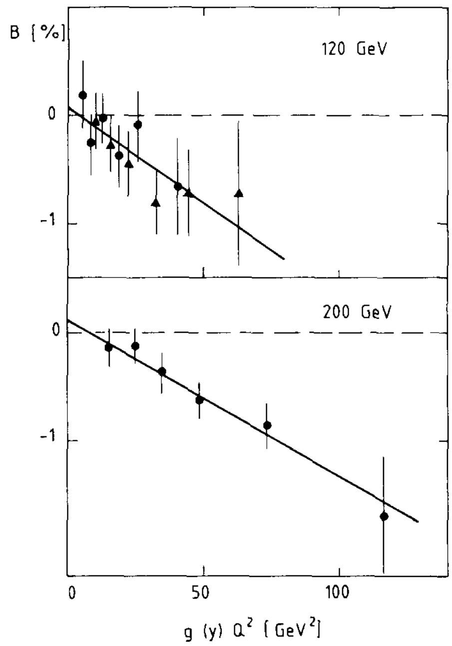

Fig. 3. The measured B asymmetry after radiative corrections at 120 GeV and 200 GeV beam energy versus $g(y)Q^2 = Q^2 \times [1-(1-y)^2]/[1+(1-y)^2]$ [eq. (3)]. For the 120 GeV data, circles represent data with $Q^2 > 15$ GeV. Solid lines are straight line fits to the data.

netic and weak-electromagnetic effects according to ref. [6]; the magnitude of these corrections is shown in fig. 2. The results for the two beam energies are presented in fig. 3 as a function of $g(y)Q^2$. Straight line fits to the two data samples, $B = a + bg(y)Q^2$, give (with statistical errors only)

200 GeV:

$a = (0.15 \pm 0.17) \times 10^{-2}$,

$b = (-0.147 \pm 0.037) \times 10^{-3}\ \mathrm{GeV}^{-2}$,

120 GeV:

$a = (0.06 \pm 0.17) \times 10^{-2}$,

$b = (-0.174 \pm 0.075) \times 10^{-3}\ \mathrm{GeV}^{-2}$.

The 120 GeV result is the average of separate fits to the two data sets. These results agree well with the standard model predictions (3) (for $\sin^2\theta_W = 0.23$) $a = 0$, $b = -0.151 \times 10^{-3}\ \mathrm{GeV}^{-2}$ at $|\lambda| = 0.81$ (200 GeV) and $b = -0.153 \times 10^{-3}\ \mathrm{GeV}^{-2}$ at $|\lambda| = 0.66$ (120 GeV).

4. Systematic errors. As instrumental sources of systematic errors we have considered the calibration uncertainty of the magnetic fields and the effect of the change of beam phase space under polarity reversal. They lead to systematic errors of $\Delta b = 0.01 \times 10^{-3}\ \mathrm{GeV}^{-2}$ (200 GeV) and $\Delta b = 0.02 \times 10^{-3}\ \mathrm{GeV}^{-2}$ (120 GeV).

Further errors arise from the natural charge asymmetry of matter: differences in halo contamination for μ^+/μ^- beams, asymmetry of muon background from meson decays, small differences in the muon energy loss and the spatial asymmetry of δ rays generated along the muon track which affect slightly the event reconstruction. From these sources, of which the first is the most important one, we estimate errors of $\Delta b = 0.02 \times 10^{-3}\ \mathrm{GeV}^{-2}$ for both data sets. The total systematic errors are $\Delta b = 0.02 \times 10^{-3}\ \mathrm{GeV}^{-2}$ for 200 GeV and $\Delta b = 0.03 \times 10^{-3}\ \mathrm{GeV}^{-2}$ for 120 GeV beam energy.

To search for possible problems inherent in the experiment, the B asymmetry has been evaluated in bins of the vertex position and of the azimuth angle. Also, the effect of kinematical cuts has been carefully studied. In all cases no fluctuations beyond the statistical ones have been observed. Evaluating the asymmetry from data samples of equal beam charge within a single data taking period gives a zero slope within statistical errors.

A check on the potential effects of systematic errors is given by the comparison of the slope parameters b measured in different data taking periods. With statistical errors only, the χ^2 per degree of freedom is smaller than 1.0 for the 120 GeV data and is equal to 2.0 for the five 200 GeV periods. In the latter case, the probability of such a χ^2 or a larger one is 10%. It increases substantially if we take into account those systematic errors which are expected to vary randomly from period to period.

To illustrate the correct interpretation of our result, we present in fig. 4 the B asymmetry calculated in kinematical variables other than $g(y)Q^2$ compared to standard model calculations with $\sin^2\theta_W = 0.23$. We remark an impressive overall agreement, in particular in the Bjorken x variable in which almost no slope is predicted by the theory but which is very sensitive to the magnetic field calibrations and other systematic effects (e.g. differences in muon energy loss) which influence the momentum reconstruction.

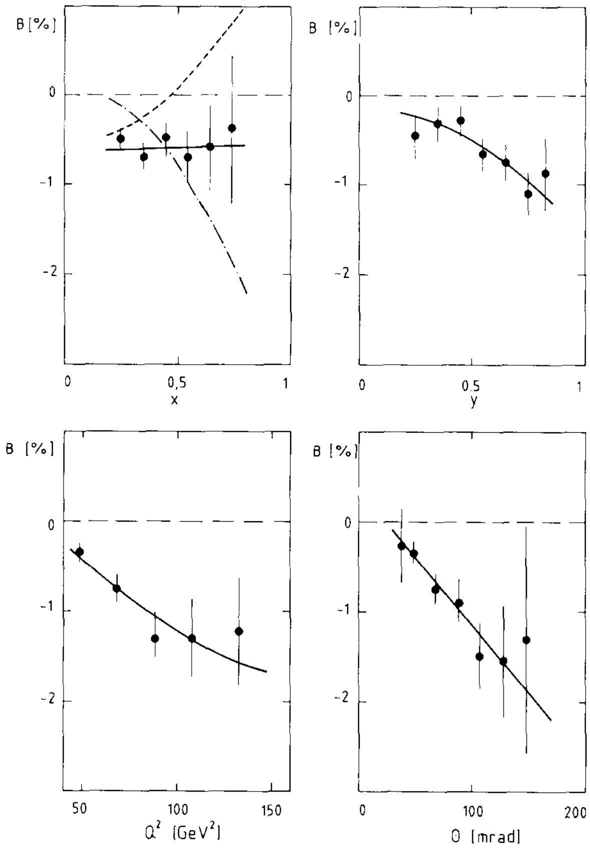

Fig. 4. The measured B asymmetry after radiative corrections at 200 GeV beam energy plotted as a function of the scaling variables x and y, Q^2, and the muon scattering angle θ. The solid lines are asymmetries predicted by the WS/GIM standard model, using $\sin^2\theta_W = 0.23$. The dashed and dashed–dotted lines in the x plot are asymmetries which would arise from a systematic relative μ^+/μ^- difference of 3×10^{-3} in the spectrometer magnetic field and the beam energy, respectively.

5. Conclusions. The interference between the weak and electromagnetic currents has been observed for the first time in the muon-quark interaction. The quantitative interpretation of the results relies on the validity of the quark parton model and the radiative corrections. The mixing angle of the standard WS/GIM model derived from the measured slope parameters b is [‡1] $\sin^2\theta_w = 0.23 \pm 0.07$ (stat.) $\pm$ 0.04 (syst.). The

[‡1] A correction for sea quarks to A_0 would increase $\sin^2\theta_W$ by 0.01.

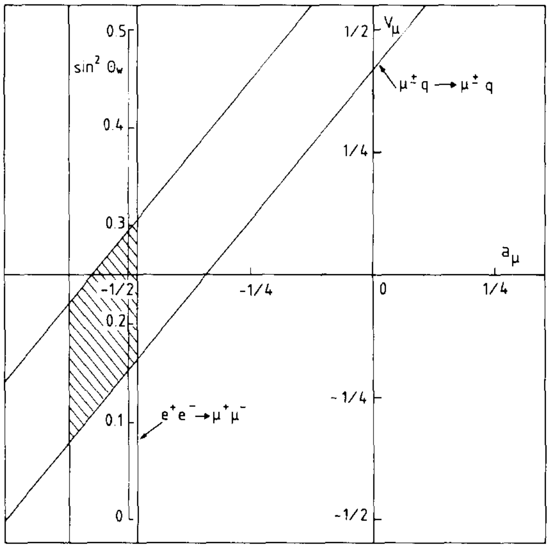

Fig. 5. Experimental limits on the muon neutral current couplings from this experiment (200 GeV data) and from $e^+e^- \to \mu^+\mu^-$ forward–backward asymmetries measured at PETRA [11]. Only statistical errors are shown.

B asymmetry measured at polarizations ≈ 1 depends strongly on the right-handed weak charge I_3^R of the muon [10]. Using $\sin^2\theta_W = 0.23$, we obtain $I_3^R = 0.00 \pm 0.06$ (stat.) $\pm$ 0.04 (syst.). This result rules out a neutral heavy lepton M^0 of any mass in a right-handed weak isospin doublet with the muon.

Assuming the quark (u, d) and electron axial vector couplings of the standard model, our experiment and the measurements of the forward–backward asymmetry in $e^+e^- \to \mu^+\mu^-$ reactions determine completely the muon neutral current couplings. As illustrated in fig. 5, both types of experiment yield complementary information: using $a_\mu = -0.55 \pm 0.07$ derived from PETRA results [11], we find $v_\mu = -0.12 \pm 0.14$ (stat.) $\pm$ 0.08 (syst.). The corresponding value of $\sin^2\theta_W = 0.19 \pm 0.07$ (stat.) $\pm$ 0.04 (syst.) is in good agreement with the values obtained in earlier ν and e experiments for the electron and quark currents.

The apparatus which proved suitable for this experiment has been conceived and its construction directed by C. Rubbia. We are indebted to the technical staff of our home institutes who contributed to the construction and maintenance of the detector and to the CERN SPS division for invaluable help in operating the muon beam and the beam momentum spectrometer. The collaboration of P.L. Frabetti, V.S. Khabarov and D.A. Smolin was indispensable to achieve the high level of stability in operating the apparatus that was essential for this measurement. Finally, we acknowledge significant contributions of G. Sultanov to the data analysis.

References

[1] F.J. Hasert et al., Phys. Lett. 46B (1973) 138;
A. Benvenuti et al., Phys. Rev. Lett. 32 (1974) 800.
[2] S.L. Glashow, Nucl. Phys. 22 (1961) 579;
A. Salam, in: Elementary particle theory, ed. N. Svartholm (Almqvist and Wiksells, Stockholm, 1969), p. 367;
S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264;
S.L. Glashow et al., Phys. Rev. D2 (1970) 1285.
[3] P.Q. Hung and J.J. Sakurai, Ann. Rev. Nucl. Part. Sci. 31 (1981) 375;
J.E. Kim et al., Rev. Mod. Phys. 53 (1981) 211.
[4] N.N. Nikolaev et al., Pisma Zh. Eksp. Teor. Fiz. 18 (1973) 70;
E. Derman, Phys. Rev. D7 (1973) 2755;
S. Berman and J. Primack, Phys. Rev. D9 (1974) 2171;
S.M. Bilenky and S.T. Petcov, JINR E2-10809 (1977).
[5] C.Y. Prescott et al., Phys. Lett. 77B (1978) 347; 84B (1979) 524.
[6] D.Yu. Bardin and N.M. Shumeiko, Yad. Fiz. 29 (1979) 969;
D.Yu. Bardin et al., Nucl. Phys. B197 (1982) 1.
[7] D. Bollini et al., Nucl. Instrum. Methods 204 (1982) 333.
[8] R. Clifft and N. Doble, CERN/Lab. II/EA/74-2, unpublished;
N. Doble, CERN/Lab. II/EA/75-17, unpublished;
O.C. Allkofer et al., Nucl. Instrum. Methods 179 (1981) 445.
[9] D. Bollini et al., Nuovo Cimento 63A (1981) 441.
[10] M. Klein et al., Phys. Lett. 85B (1979) 385.
[11] W. Bartel et al., Phys. Lett. 108B (1982) 140;
R. Brandelik et al., Phys. Lett. 110B (1982) 173;
B. Adeva et al., Phys. Rev. Lett. 48 (1982) 1701;
M. Davier, Proc. 21th Intern. Conf. on High energy physics (Paris, 1982), to be published.