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E1-82-656

CHARGE ASYMMETRY IN $\mu^{\pm}N$ DEEP INELASTIC SCATTERING

BCDMS Collaboration

Presented by Črtomir Zupančič
at the International Neutrino Conference,
Balatonfüred, Hungary, 14-19 June 1982

1982

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1. INTRODUCTION

The discovery of weak neutral currents in νN interactions [1] in 1973 triggered both experimental and theoretical efforts to study their structure in detail. The experiments done since then on νN, νe, eN scattering and e^+e^- annihilation are in good agreement with the predictions of the standard WS-GIM model [2] of electroweak interactions. Still, it is considered important [3,4] to test the model in new kinematical regions and reaction channels.

In order to measure the effect of the Z° exchange interfering with the dominant one-photon exchange and check the prediction of the WS-GIM model, the Bologna-CERN-Dubna-München-Saclay collaboration (CERN NA4 experiment) has measured the deep inelastic scattering of positive and negative muons on nucleons in an isoscalar carbon target

$$\mu^\pm N \to \mu^\pm + \dots$$

at two incident energies 120 and 200 GeV. This experiment differs from the SLAC e^-D experiment [5] in that both the helicity and the charge of the muon are simultaneously reversed (by reversing the polarities of all magnets in the experiment), i.e., we measure the asymmetry $B(u,v,\lambda)$ defined as

$$B(u,v,\lambda) = \frac{\dfrac{d^2\sigma^+(-\lambda)}{du\,dv} - \dfrac{d^2\sigma^-(\lambda)}{du\,dv}}{\dfrac{d^2\sigma^+(-\lambda)}{du\,dv} + \dfrac{d^2\sigma^-(\lambda)}{du\,dv}}, \qquad (1)$$

where $\frac{d^2\sigma^\pm}{du\,dv}$ are the doubly differential cross sections of positively and negatively charged muons with respect to two convenient kinematical variables u and v characterizing the scattered muon, while λ is the average longitudinal polarization of the negative muon beam. In order to present data of limited statistics, it is convenient to integrate the doubly differential cross sections with respect to one or even both kinematical variables, thus arriving at the asymmetries $B(u,\lambda)$ and $B_{tot}(\lambda)$ defined in complete analogy to expression (1). The domain of integration is determined by the acceptance of the apparatus and the kinematical cuts applied to the data.

If one takes into account only the one photon and the one single Z^0 exchange graph, the asymmetry $B(u,v,\lambda)$ is equal to[6]

$$B(u,v,\lambda) = -K(a_\mu - \lambda v_\mu) A_0 w \quad . \qquad (2)$$

The quantity $K = \frac{G}{\sqrt{2}} \frac{1}{2\pi\alpha}$ (G - Fermi constant, α - fine structure constant), equal to $1.80 \cdot 10^{-4}$ GeV^{-2}, characterizes the strength of the γZ^0 interference. In principle, the asymmetry B contains terms higher than linear in K which have been neglected in expression (2). A_0 is defined as the ratio of structure functions G_3 and F_2, i.e.,

$$A_0 = \frac{x G_3(x, Q^2)}{F_2(x, Q^2)} .$$

The definition of G_3 and F_2 is given in ref.[6] Q^2 is the four momentum transfer and x is the Bjorken scaling variable

$$x = \frac{Q^2}{2M(E_0 - p)} ,$$

where E_0 is the incident muon energy, p is the scattered muon energy and M is the proton mass. In the parton model, for an isoscalar target, A_0 reduces to a constant, namely

$$A_0 = \frac{6}{5}(a_d - 2a_u),$$

the quantities a_d and a_u being the axial coupling constants of the Z^0 to the d and u quark, respectively. Similarly, a_μ and v_μ in expression (2) are the axial and vector coupling constants of the Z^0 to the negative muon. Without restricting the muon to any specific weak isospin I_3, we can write

$$a_\mu - \lambda v_\mu = I_3^L (1-\lambda) - I_3^R (1+\lambda) - 2\lambda \sin^2\theta_w ,$$

L and R labelling the left- and right-handed muon, respectively, and θ_w being the Weinberg angle. The asymmetry $B(u,v,\lambda)$ is thus proportional to a single kinematical variable w defined as

$$w = g(y) Q^2 = \frac{1-(1-y)^2}{1+(1-y)^2} Q^2 ,$$

where $1-y = p/E_0$.

Notice that the asymmetry B contains both a parity violating term $v_\mu A_0$ and a parity conserving term $a_\mu A_0$. In the standard model with $I_3^R(\mu) = 0$ and the present world average value of $\sin^2\theta_w = 0.23$, the vector coupling constant v_μ is small and the parity conserving term dominates. In this case, the asymmetry B is negative for any value of λ.

It has been shown[7,8] that higher order electroweak terms ("radiative effects") make an important positive contribution to the asymmetry B and thus tend to decrease it in absolute value (e.g., by ~40% at an incident energy of 200 GeV and by ~80% at 120 GeV).

2. APPARATUS

The NA4 spectrometer is situated in the CERN SPS muon beam behind the apparatus of the European Muon Collaboration[9]. The muon beam is operated with the average muon energy 20 GeV lower than the average energy of the parent pions and kaons. At 200 GeV this yields maximum intensity and leads to a calculated[10] absolute value of average polarization $|\lambda| = 0.81 \pm 0.04$. The measured[11] polarization at 200 GeV agrees with the calculated value within experimental and computational errors. At 120 GeV the calculated average polarization is $|\lambda| = 0.66 \pm 0.05$.

The general layout of the NA4 spectrometer is shown in fig.1. It consists of a ca.50 m long torus of iron magnetized to saturation (ca. 2 T) with targets located in the central bore. Muons of the same charge as the incident beam are focused by the magnetic field and perform periodical oscillations inside the iron with amplitudes proportional to $Q^2/Q^2_{max} = Q^2/(2ME_0)$. The spectrometer is subdivided into ten identical supermodules. Each supermodule consists of:

(a) a separate carbon target 5 m long and 12 cm in diameter (except in the last two supermodules);
(b) 32 iron disks (each 11 cm thick) magnetized by a common coil;
(c) two trigger counter planes, each consisting of seven concentric rings with constant radial width and separation which make Q^2-selective triggering possible;
(d) eight planes of multiwire proportional chambers (MWPC) to determine the muon trajectory. Alternating planes measure the x and y coordinates of the track with a channel width of 4 mm (the spectrometer axis is defined as the z-axis).

For the asymmetry measurement the spectrometer possesses the important advantages of high luminosity, large redundancy, and high degree of azimuthal symmetry.

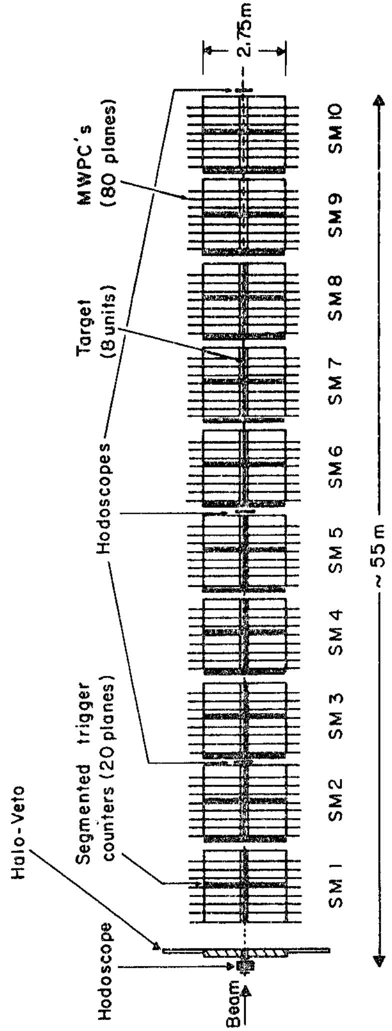

Fig.1. Schematic view of the NA4 spectrometer.

About 130 m upstream of our apparatus are not shown in fig.1, a beam momentum station (BMS) consisting of beam deflecting magnets and hodoscopes measures the energy of each incident muon with a resolution of 0.5%. Hits in the BMS hodoscopes can be correlated in time (to about 1 ns) with hits in the three beam hodoscopes (each consisting of 72 scintillators in five concentric rings) shown in fig.1, as well as with the trigger counter planes (to about 10 ns). The first of the beam hodoscopes monitors the beam flux and is also used in the trigger logic. The apparatus is shielded against the beam halo muons by a veto system of scintillation counters.

3. DATA TAKING, ANALYSIS, AND RESULTS WITH STATISTICAL ERRORS

Data for the B asymmetry were taken at two incident energies 200 GeV and 120 GeV at approximately constant beam intensity of $2\cdot 10^7\ \mu$/spill in eight periods of 12 days each. The polarities of all magnets were reversed typically twice during a period; substantially more frequent reversals were not feasible considering that each took several hours and necessitated a resharing of the SPS proton beam.

The standard trigger condition for data taking required the coincidence of four consecutive trigger planes (~11 m long track) and the beam-halo signal. This trigger detects interactions wherever they occur along the effective target length of ca. 36 m. Part of the 120 GeV data (one period) were taken with full planes (rings 1-7) in the trigger, corresponding to $Q^2/Q^2_{max} \gtrsim 0.05$, while the remaining 120 GeV data (two periods) and all 200 GeV data (five periods) were taken with ring 1 excluded from the trigger. The latter condition reduces the triggering rate due to showers and leads to $Q^2/Q^2_{max} \geq 0.1$.

The data were processed with a standard program [12] using automatic selection of deep inelastic events which represent typically 10% of all triggers. A few per cent of dubious candidates for deep inelastic events were visually scanned and about half of these were rejected as being mainly halo feed-through muons. Crude stability checks were applied to consecutive samples of data containing several thousands deep inelastic events each. These checks concerned beam energy, detector efficiencies, number of events per incoming flux, average values of kinematical quantities such as scattered momentum and Q^2, etc. About 15% of the samples did not pass these checks. Finally, the following cuts were applied to the data in order to avoid regions of rapidly varying acceptance and poor resolution:

	200 GeV	120 GeV(rings 2-7)	120 GeV(rings 1-7)
Q^2_{min}	40 GeV^2	25 GeV^2	12.5 GeV^2
Q^2_{max}	180 GeV^2	120 GeV^2	120 GeV^2
x_{min}	.2	.3	.14
x_{max}	.8	.8	.8
y_{min}	.2	.2	.1
y_{max}	.9	.8	.8

These and similar cuts tried for test purposes do not change the resulting B by more than one standard deviation/13/.

The remaining data contain the following number of deep inelastic events (in millions)

	200 GeV	120 GeV (rings 2-7)	120 GeV (rings 1-7)
μ^+	0.67	0.31	0.46
μ^-	0.88	0.30	0.49

We have investigated the dependence of B_{tot} on geometrical variables such as the vertex coordinate z_v and the azimuthal angle ϕ of the scattered muon and found it constant within statistical errors. The distribution of events at 200 GeV as function of the variable $w = g(y)Q^2$ and the resulting asymmetry are presented in fig.2. The asymmetries B are presented in fig.3 as function of w , p , x and Q^2, both for 200 GeV and 120 GeV (rings 2-7) data, corrected for radiative effects. The experimental acceptance and resolution have been taken into account in the calculations. The errors (vertical bars) in figs.2 and 3 are only statistical.

The relative +/- normalization reflects itself best in the total asymmetry B_{tot} . In all three cases (200 GeV, 120 GeV rings 2-7, and 120 GeV rings 1-7) the experimental B_{tot} agrees within the statistical error of about 0.1% with the theoretical B_{tot} as predicted by the standard model and radiative corrections.

4. SYSTEMATIC ERRORS

Systematic errors can arise because of imperfect time stability of the apparatus, imperfect polarity reversal of magnets,

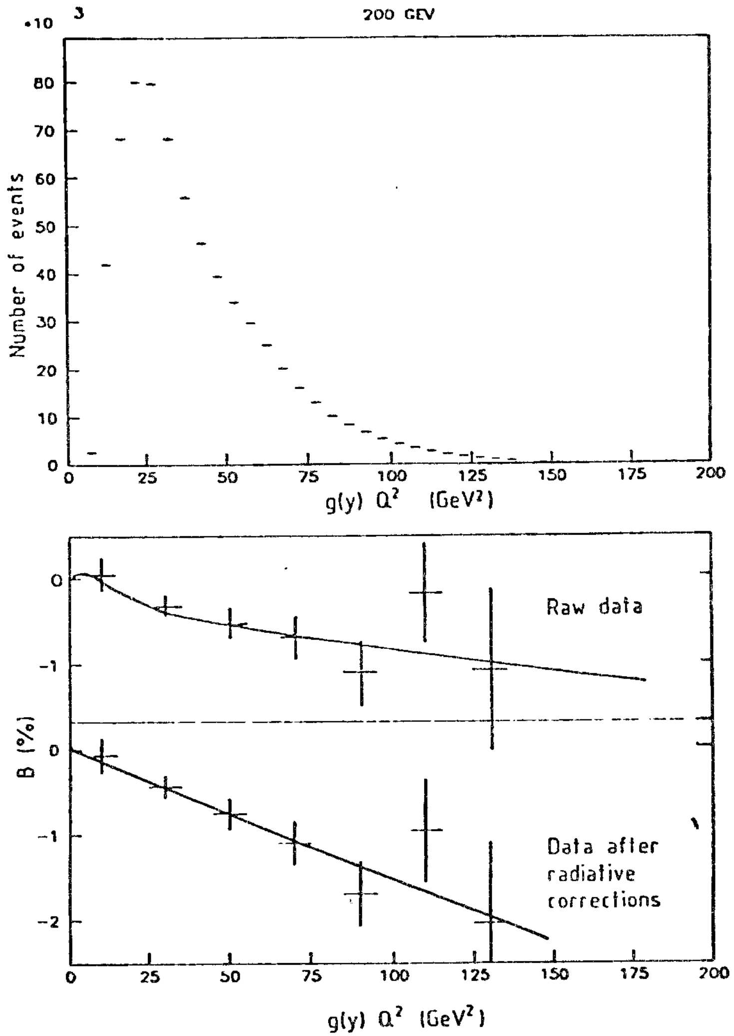

Fig.2. Distribution of μ^+ events (upper part) and the asymmetry (lower part) as a function of $w = g(y)Q^2$ at 200 GeV. The raw asymmetry data and data corrected for radiative effects are compared to corresponding predictions of the standard model (solid lines).

side effects of this reversal (e.g., change in beam phase space, change of detector efficiencies), and natural asymmetries other than B (due to the fact that matter consists predominantly of electrons, u -quarks and d -quarks rather than their antipartic-

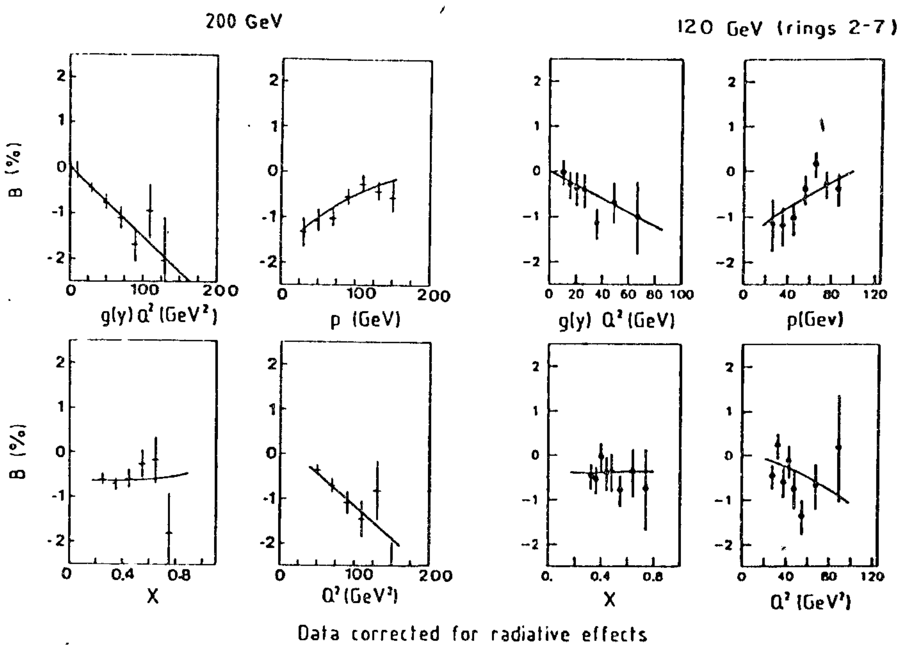

Fig.3. The asymmetry B as a function of $w = g(y)Q^2$, p, x and Q^2 at 200 GeV and 120 GeV (rings 2-7). Data are compared to predictions of the standard model (solid lines).

les). The study of systematic errors and the application of the corresponding corrections to raw data is in progress and only a brief preliminary discussion and estimates can be given here.

An objective way of determining the stochastic part of the systematic error is to repeatedly measure B and calculate the χ^2 of the results. Data as presented in fig.3 were fitted with the two-parametric form $B(w,\lambda) = a(\lambda) + b(\lambda)\,w$. The slope parameter b(0.81) was obtained separately for the five 200 GeV data taking periods. From the spread of results a total stochastic error was determined with the result:

$$b(0.81) = (-1.6 \pm 0.5) \cdot 10^{-4}\ \mathrm{GeV}^{-2}.$$

The statistical error alone amounts to $\Delta b_{stat} = 0.3 \cdot 10^{-4}\ \mathrm{GeV}^{-2}$. The two 120 GeV (rings 2-7) periods yield values of b(0.66) differing from each other only by a fraction of the statistical error with the result

$$b(0.66) = (-2.4 \pm 0.9)\ 10^{-4}\ \mathrm{GeV}^{-2}.$$

Finally, the single 120 GeV (rings 1-7) period yields

$$b(0.66) = (-1.7 \pm 1.1) \cdot 10^{-4}\ \mathrm{GeV}^{-2}.$$

These three b-values are clearly all mutually compatible and also compatible with the standard model prediction

$$b(\lambda) = (-1.61 + 0.13\,\lambda) \cdot 10^{-4}\ \mathrm{GeV}^{-2}.$$

An analogous variation of results beyond statistical errors is observed in B_{tot} for the five periods at 200 GeV, leading to a fluctuating systematic error of 0.2% in B_{tot}. For this reason we have not yet exploited B_{tot} to reduce the error on $b(\lambda)$ by effectively determining it from a one-parameter fit.

Another indication of comparable time fluctuating systematic error in the 200 GeV data is obtained by calculating the apparent asymmetry between any two sets of data with equal sign muons, separated by data taken at opposite polarity (i.e., also by a large time interval).

Efforts are in progress to reduce or eliminate the sources of fluctuating systematic errors. At present, not even the straightforward corrections for varying trigger counter, MWPC and electronic efficiencies have been applied to the data.

Compared to the stochastic errors, the systematic errors arising from imperfect polarity reversal and its side effects and from natural asymmetries are estimated to be small. The spectrometer magnetic field was reversed on a constant computer controlled hysteresis curve with a relative uncertainty of $2 \cdot 10^{-4}$ determined from the analysis of induction loop and Hall probe measurements as well as iron temperature monitoring. The relative uncertainty on the equality of μ^+ and μ^- incident energies is at present $6 \cdot 10^{-4}$, as derived from the time stability of the spatial position and electronic performance of the BMS hodoscopes and the monitoring of BMS magnetic fields by Hall probes. The phase space regions of the muon beams with opposite polarity differed imperceptibly from each other. These three sources of error together cause a systematic error $\Delta b_{rev.1} \leq 0.05 \cdot 10^{-4}\ \mathrm{GeV}^{-2}$.

We have indications that the detection efficiencies (trigger counters, MWPC, and electronics) shift slightly when the polarity is reversed. Until the corresponding corrections are applied the additional systematic error on the slope parameter is estimated at $\Delta b_{rev.2} \leq 0.13 \cdot 10^{-4}\ \mathrm{GeV}^{-2}$.

The natural asymmetries considered and studied comprise the charge asymmetry of halo contaminating the deep inelastic events, the charge asymmetry of hadronic and electromagnetic showers produced both in the carbon target and the iron of the spectrometer, the resulting asymmetry of muons produced in the decay of the hadronic shower component, and the asymmetry of stopping power of muons in matter. The best present estimate of systematic error due to these asymmetries is $\Delta b_{nature} \lesssim 0.13 \cdot 10^{-4}\,GeV^{-2}$.

5. CONCLUSIONS

The observed asymmetry in deep inelastic scattering of oppositely polarized positive and negative muons on a carbon target is within experimental errors correctly described by:

1. the standard WS-GIM model with $\sin^2\theta_W = 0.23$,
2. the radiative corrections of Bardin and Shumeiko,
3. the quark parton model used in part of the radiative correction calculations and in the evaluation of the nucleon structure function ratio A_0.

Specifically, fitting an arbitrary weak isospin $I_3^R(\mu)$ to the data under the latter two assumptions yields $I_3^R(\mu) = 0.04 \pm 0.07 \pm 0.03$ as the weighted average of the results obtained at 200 GeV, 120 GeV (rings 2-7), and 120 GeV (rings 1-7). The first error is stochastic, the second is due to uncertainties about polarity reversal and natural asymmetries.

On the other hand, with the latter two assumptions and $I_3^R(\mu) = 0$, the best fits to $\sin^2\theta_W$ yield as the weighted average $\sin^2\theta_W = 0.28 \pm 0.08 \pm 0.04$.

Finally, assuming the correctness of the standard model and of the A_0-value, the radiative corrections of Bardin and Shumeiko are experimentally confirmed within a factor of about 1.5.

Of course, an accidental cancellation of potential deviations from the above assumptions is always possible. We consider the results of our experiment as a consistency check on these assumptions to be viewed in connection with all other experimental information on the subject.

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Received by Publishing Department
on September 8 1982.

Арджento А. и др. E1-82-656
Зарядовая асимметрия в глубоконеупругом $\mu^{\pm}N$-рассеянии

БЦДМС сотрудничество /НА-4 эксперимент в ЦЕРНе/ получило данные для измерения асимметрии в глубоконеупругом рассеянии μ^{+}- и μ^{-}- пучков на углеродной мишени. Это измерение может проверить структуру слабого нейтрального тока и установить предел по слабому изоспину для правовинтового мюона. В настоящее время продолжается анализ трех миллионов событий, накопленных при энергиях пучков 120 и 200 ГэВ. На нынешнем уровне понимания данные находятся в согласии с предсказаниями стандартной ВС-ГИМ модели.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1982

Argento A. et al. E1-82-656
Charge Asymmetry in $\mu^{\pm}N$ Deep Inelastic Scattering

The BCDMS Collaboration (CERN NA4 experiment) has taken data to measure the asymmetry in the deep inelastic scattering of μ^{+} and μ^{-} beams incident on a carbon target. This measurement can check the structure of the neutral weak current and set a limit on the weak isospin of the right-handed muon. The analysis of over 3 million events taken at 120 and 200 GeV is in progress. At the present level of understanding the data are in agreement with the standard WS-GIM model.

The investigation has been performed at the Laboratory of High Energies, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1982