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ABSTRACT

The $K^0_{\mu 3}$ charge asymmetry has been measured to be $(6.0 \pm 1.4) \times 10^{-3}$. The error contains a major systematic contribution. Large corrections were made in order to exclude neutron-induced background events and to correct for the range difference between μ^+ and μ^-.

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The charge asymmetries in the semileptonic decays $K_L^0 \rightarrow \pi^{\mp} \ell^{\pm} \nu$ are the only known manifestations of CP violation aside from the decays $K_L^0 \rightarrow \pi\pi$. Assuming CPT invariance and that the semileptonic decays proceed by first-order weak interactions only [1], it is possible to relate the charge asymmetries to ϵ, the CP mixture parameter of the neutral K-meson states, and to x_ℓ, the $\Delta S = \Delta Q$ violation parameter [2]:

$$\delta_\ell = (\Gamma_+ - \Gamma_-)/(\Gamma_+ + \Gamma_-) = 2 \ \mathrm{Re}\ \epsilon\ F_\ell,$$

$$F_\ell = (1 - |x_\ell|^2)/ |1 - x_\ell|^2 .$$

Here $\Gamma_\pm$ is the rate for decay to $\pi^{\mp} \ell^{\pm} \nu$ (ℓ is either a muon or an electron). If the $\Delta S = \Delta Q$ rule holds in weak interactions, F_ℓ is equal to 1 and $\mathrm{Re}\ \epsilon = (\delta_\ell/2)$.

We report a new measurement of the muonic charge asymmetry [3]. The result of this experiment should be compared to the previous result for the $K_{\mu 3}^0$ asymmetry [4], the best value of the K_{e3}^0 asymmetry [5], and the prediction of the superweak theory [6]:

this experiment: $\delta_\mu = (6.0 \pm 1.4) \times 10^{-3}$,

previous $K_{\mu 3}^0$: $\delta_\mu = (5.7 \pm 1.7) \times 10^{-3}$,

best value K_{e3}^0: $\delta_e = (3.22 \pm 0.29) \times 10^{-3}$,

superweak theory: $\delta = (2.80 \pm 0.08) \times 10^{-3}$.

The superweak prediction holds for both charge asymmetries if the $\Delta S = \Delta Q$ rule is valid.

From the K_{e3}^0 charge asymmetry measurements and a measurement [7] which yielded $F_e = (0.96 \pm 0.05)$, we obtain:

$$F_\mu = (\delta_\mu/\delta_e) F_e = 1.79 \pm 0.46.$$

A difference between F_μ and F_e would not necessarily violate μ-e universality because the F's could depend on the lepton mass, for example through the well-known presence of the f_- form factor, which is important only in the muonic decay mode. If we assume that $Im(x_\mu)=0$, as is consistent with the previous measurements [8] of x_μ and as is implied by T invariance in the muonic decay interaction, we obtain $Re(x_\mu) = 0.27 \pm 0.12$.

The experiment was located at the end of the second channel of the external proton beam at the Lawrence Berkeley Laboratory's Bevatron. The 7° neutral beam (solid angle about 0.2 msr) was defined by a series of tapered collimators and by four sweeping magnets. The detection apparatus [9] consisted of 154 scintillation counters (fig. 1) monitored by a PDP-9 computer. K_L^0 decays were identified by an up-down coincidence of the large trigger counters "P" situated outside the neutral beam. The $K_{\mu 3}^0$ component was identified by requiring muons to penetrate a 61 cm lead wall. The system was up-down symmetric: the pion could be up and the muon down, or vice versa. The system was designed to accept $K_{\mu 3}^0$ decays which had a vertex in the decay volume and produced a muon with sufficient momentum to penetrate the lead wall, but for which both the muon and the pion had sufficient transverse momentum to get out of the beam (i. e., cross over the beamside edge of the appropriate P counter). The expected muon track would contain P, S, R, T, L, M and perhaps N counts. The presence of a pion was indicated by a P count opposite the muon track. Additional counts farther downstream might occur when the pion stayed close to the beam.

The charge-resolving magnet (M5) imparted a transverse momentum of about 500 MeV/c to the particles passing through it. Since the maximum transverse momentum of a muon in $K^0_{\mu 3}$ decay is 216 MeV/c, μ^- were given a complete angular separation from μ^+. One method of muon charge determination was to observe the muon position at the L hodoscope. In the absence of multiple scattering this method would have been completely unambiguous. The charge was also determined by measuring the muon bend angle in the M5 magnet, using the S, R, and T hodoscopes (fig. 1). The S-R-T determination was often ambiguous if an extra counter were on, or if a track had high enough momentum that it looked essentially straight in the apparatus. The charge determination was excellent; as a fraction of the total number of events, only 0.3% had a disagreement between the two methods. The S-R-T method was chosen to determine the muon charge when possible. Where the S-R-T method failed, the L method was used. The wrong charge was chosen for only about 10^{-6} of the events in the final sample.

The ratio of high-energy neutrons to long-lived K mesons in the neutral beam was large, about 200:1. In order to avoid contamination by neutron interactions, all mass was removed from the neutral beam in the decay volume. The anti counter (A in fig. 1), actually a set of six counters, was logically equivalent to a single large counter with a hole in it slightly larger than the beam. An event was accepted only if counts were observed in both P counters but not in the anti counter. The entire decay volume was kept at vacuum (typically 10^{-2} torr), and the A, P, and C counters were inside the vacuum tank.

Frequent reversal of the charge-resolving magnetic field was relied upon to cancel the effect of possible geometrical biases. The magnetic field was reversed approximately every 10 000 events. A major advantage of having used only counters is that their counting efficiency was measured very accurately. We have demonstrated that their counting efficiency did not change with magnetic field reversal to an accuracy of one part in 10^4.

The $K^0_{\mu 3}$ signature criterion was satisfied by 9 million events. Of these, about 5 million were taken in the normal configuration, and the remaining 4 million were taken with mass added in various portions of the apparatus. After all cuts and randoms subtractions, 4.1 million normal events remained.

There were two known flaws in the trigger system. First, neutrons in the beam halo could have interacted in the anti counter itself. If charged particles were produced sufficiently close to the downstream anti-counter edge, the particles would not have registered. If these charged particles also counted in both P counters, such a neutron-induced event would have been accepted. To measure this effect, scintillator was placed just downstream of the anti counters, to increase the inactive volume. A linear extrapolation was then made to zero mass. The measured correction to the charge asymmetry is $(3.8 \pm 1.7) \times 10^{-4}$.

The second source of error in the trigger system was that it did not take into account neutron backscatter. Halo neutrons could have interacted in the walls of the downstream vacuum snout and sprayed low energy particles backward into both P counters. To measure the number and charge asymmetry of such events, the walls of the snout were lined with counters (labeled C, fig. 1). Counters also were placed below P_{up} and above P_{down} to detect interactions in the P's themselves. For a neutron interaction to have backscattered from the snout into both P's, both an upper C and a lower C must have counted. This was true even if the interaction occurred in a C counter. Another means of detecting neutron interactions in the snout was the counter labeled S_{V1}, nearest the beam on the muon side next to the downstream snout (fig. 1).

The main event category ("single-track events") was that in which no ambiguities occurred in the counters comprising the muon track. To demonstrate the effect of the C coincidence on these events, fig. 2 shows the distributions of the number of events and charge asymmetry vs. muon bend angle for single-track events with and without a C coincidence. Neutron contamination is evident. There is a very large charge asymmetry in the small bend angle (high momentum) bins, where very few muons are expected from $K^0_{\mu 3}$. A strong correlation between the asymmetric events and the C coincidence is seen, indicating that many of these events originated in the snout downstream of the vacuum tank. Apparently, the culprit was the type of neutron interaction in which a high-momentum hadron penetrated the lead wall. These events appear to have left uncontaminated much of the region where the real muons are expected (bend angle bins 0.24 to 0.48). The asymmetric events with no C coincidence are due to neutron interactions in the anti counter, and are treated by the anti mass extrapolation.

The low momentum events in fig. 2 also show a charge asymmetry correlated with the C coincidence. However, these events represent no problem; there are so few of them that their effect on the charge asymmetry is less than 10^{-4}.

The data also reveal a marked difference between the events in which counter S_{V1} did and did not fire. The correlation of S_{V1} events with the C-coincidence events was very high at the small muon bend angles. Using these two means of identification of "neutron" events, a cut was made in the muon bend angle distribution: the cut eliminates all events with bend angle ≤ 0.18, and all events in bin 0.24 with both C coincidence and counter S_{V1}. After this "neutron cut," the charge asymmetry of the remaining events (or any portion of them) was found to be independent of the state of the C coincidence to an accuracy equal to the statistical error of the sample. We have therefore assigned a systematic error of $\pm 5 \times 10^{-4}$, equal to the statistical error, to our ability to exclude the effects of neutron interactions with this cut.

The effectiveness of the neutron cut is obviously due to the fact that most of the neutron interactions which triggered the system were associated with a hadron penetrating the lead wall; such a penetration apparently required a much higher momentum than was required for a muon penetration.

Multiple-track events (i. e., events with an ambiguity in the muon track) constituted 10.8% of the data. In order to be sure to exclude the high-momentum neutron-induced events, when an ambiguity in the bend angle arose, the track combination with the smallest bend angle was chosen to represent the event. This procedure, though necessary, caused serious problems in the analysis of events with knock-on electrons.

Consider a μ^- which makes a knock-on in the R counters, inside the M5 magnet. The electron will spiral around in the magnetic field and, if it has sufficient energy, it may count in an R bin separate from that of the muon. Since the knock-on has the same charge as the μ^-, it will always spiral in the same direction as the muon bends. Hence, the track including the knock-on will always appear to have a higher momentum (less curvature) than the real μ^- track. By the same reasoning, a μ^+ can only produce a knock-on track with apparently lower momentum. Due to the above analysis procedure, knock-ons will shift μ^- events to smaller bend angles but will leave μ^+ events in their proper bins. Then the neutron cut preferentially excludes μ^- when applied to such events.

The knock-on effect was studied by isolating various categories of events with knock-on-type counter configurations (e. g., one extra R counter firing). A scatter plot of charge asymmetry vs largest and smallest bend angle for events with an extra R count shows very strong knock-on-type correlations. About half of these events were due to knock-ons. Before the neutron cut, the charge asymmetry of these events was about the same as that of the main data, but after the neutron cut the charge asymmetry rose to about 20%. Consequently we can to a high degree of accuracy measure the knock-on correction for such events by assuming that their entire charge asymmetry is due to exclusion of μ^- knock-on events by the neutron cut. In this manner the knock-on correction was measured to be 5.03×10^{-3}.

Knock-ons in the R bank were also studied with a Monte Carlo calculation. The Monte Carlo was successful in predicting all relevant distributions and gave a knock-on correction of 4.06×10^{-3}. The final knock-on correction to the charge asymmetry of $(4.54 \pm 0.5) \times 10^{-3}$ was taken to be the average of the Monte Carlo and measured values with a systematic error of half the difference.

The system was triggered on $K^0_{\mu 3}$ events and also on the two random configurations which were most important: a muon track with a random pion P count, and a decay vertex with a random LM signal behind the lead wall. For each trigger, bits were recorded and sent to the computer not only in real time, but also in correlated delayed time (403 ns later, the time of one Bevatron revolution). The probability that a counter was on in the delayed time interval was typically 0.3%. It is believed that the randoms subtractions were measured to a systematic accuracy of ± 5%. However, because of small effects in some random configurations which were not measured directly, the error has been increased to $\pm 2 \times 10^{-4}$ (± 15% of the correction). The statistical error of the randoms subtraction is negligible ($\sim 10^{-5}$), and the correction to the asymmetry for random-trigger events is $(-12.1 \pm 2.0) \times 10^{-4}$. The random-trigger events have been implicitly subtracted (bin-by-bin where applicable) throughout this paper.

In order to measure the charge asymmetry in the absorption of $K^0_{\mu 3}$ pions before they could traverse the inactive length of a P counter, mass was added upstream of the P counters, and a linear extrapolation was performed to zero mass. The straight-line fit is good and the charge asymmetry correction is $(+0.9 \pm 3.6) \times 10^{-4}$.

The possibility of charge-asymmetric penetration of the lead wall by pions from K^0_L decay was studied by examining events with extra counters on behind the lead wall. Our experience with the neutron-induced hadrons which penetrated the lead wall indicated that a significant number of such hadrons produced extra counts after penetration. After the neutron cut, however, the events with such extra counts had no statistically significant charge asymmetry. If a pion-penetration correction were necessary, we should have observed an asymmetry in these events. Consequently we have made no correction to our result because of pion penetration.

A Monte Carlo calculation predicts that $14 \pm 2\%$ of the events were actually due to pion decay in flight. The mechanism was K^0_L decay to a mode yielding two charged particles into the acceptance; one of these would be a π, which subsequently decayed to a μ, which in turn penetrated the lead wall.

Using measured differences between π^+ and π^- cross-sections, we found that the calculated change in the charge asymmetry from differential $\pi^{\pm}$ absorption before decay is negligible (about 10^{-4}). Hence the correction for asymmetric events caused by decay-in-flight is entirely due to the CP-violating asymmetry in $K^0_{\mu 3}$ and K^0_{e3} decay. The charge asymmetry correction is $(5.7 \pm 1.0) \times 10^{-4}$. An additional correction was necessary (see Table I) because of the dilution of the event sample by decays in flight.

A bias on the charge asymmetry was created by mu-mesic x-rays produced when μ^- stopped in the iron just upstream of the last required counter bank (M). Essentially all stopped μ^- produced such an x-ray well within the 15 ns sensitive time. [10] The efficiencies for detecting these x-rays in the M counters were calculated for the relevant transitions in iron [11]. The main source of uncertainty is the lack of precise knowledge of the threshold of the M counters. The correction to the charge asymmetry was found to be $(+3.9 \pm 1.5) \times 10^{-4}$.

A difference in the ionization losses and hence in the ranges of μ^+ and μ^- as they traverse material has recently been calculated [12] and measured. [13] According to the theory, the fractional range difference $[(R_- - R_+)/R]$ for momenta of interest in this experiment (1.1 to 1.5 GeV/c) is nearly constant at about 2×10^{-3}. Using the value of 1290 MeV/c (calculated by Monte Carlo) for the average initial momentum of muons stopping near the last required hodoscope (M bank), and assigning a ±4% accuracy to the theory, we find $(R_- - R_+)$ $= (1.63 \pm 0.08)$ g/cm^2 of iron.

The fraction of muons which either stopped in the last steel plate between the M and N hodoscopes or otherwise missed the N hodoscope (fig. 1) was measured to be (0.293 ± 0.004). The Monte Carlo prediction with its statistical error was (0.265 ± 0.006). Hence the prediction was correct to within 10%. The Monte Carlo was then used to extrapolate the measured data to determine the number of muons stopping in the last 1.63 g/cm^2 of the steel plate just before the M bank. This leads to a charge asymmetry correction of $(31 \pm 7) \times 10^{-4}$. The error is due mainly to an estimate of the possible systematic effects in the Monte Carlo calculation.

The $K^0_{\mu 3}$ charge asymmetry is determined as shown in Table I. The systematic errors are to be interpreted as one standard deviation. Since the correlations among the corrections are believed to be insignificant, the errors are combined in quadrature to yield:

$$\delta = (6.0 \pm 1.4) \times 10^{-3}.$$

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2. $x_\ell = \langle \pi^- \ell^+ \nu \, | H_w | \overline{K}^0 \rangle / \langle \pi^- \ell^+ \nu | H_w | K^0 \rangle$. The phase of x_ℓ is defined by the fact that $|K_2^0\rangle = (|K^0\rangle - |\overline{K}^0\rangle)/\sqrt{2}$ has CP = - 1.

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Table I. Determination of the charge asymmetry (all numbers in units of 10^{-4}). The errors under "total" are the results of combining the numbers in the individual columns in quadrature.

	Value	Errors Statistical	Errors Systematic
After neutron cut	$\delta = +51.6$	± 4.9	± 5.0
Knock-ons	$\Delta\delta = -45.4$		± 5.1
Anti mass	$\Delta\delta = +\ 3.8$	± 1.2	± 1.2
Randoms	$\Delta\delta$ included		± 2.0
P mass	$\Delta\delta = +\ 0.9$	± 3.6	
$\pi^{\pm}$ Penetration	$\Delta\delta$ = none		
Decay in flight			
asymmetry	$\Delta\delta = +\ 5.7$		± 1.0
dilution	$\Delta\delta = +\ 8.2$		± 7.1
$\mu^{\pm}$ Range difference	$\Delta\delta = +31.0$		± 7.0
$\mu^{\pm}$ End of range	$\Delta\delta = +\ 3.9$		± 1.5
TOTAL	$\delta = +59.7$	± 6.2	± 12.6

FIGURE LEGENDS

Fig. 1. Layout of the experimental apparatus.

Fig. 2. Number of single-track events and charge asymmetry vs bend angle. NCC = events without C-coincidence. CC = events with C-coincidence.

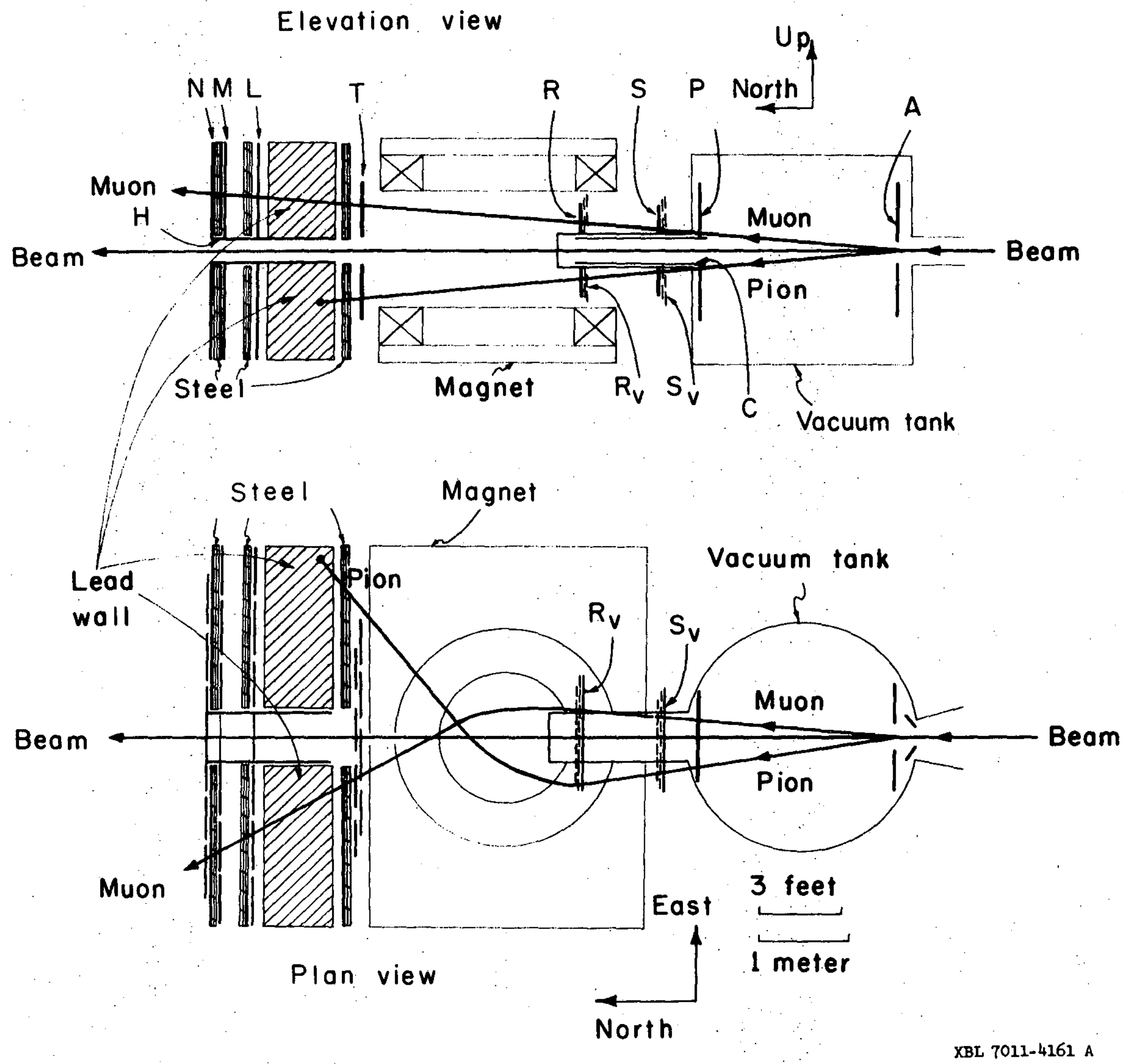
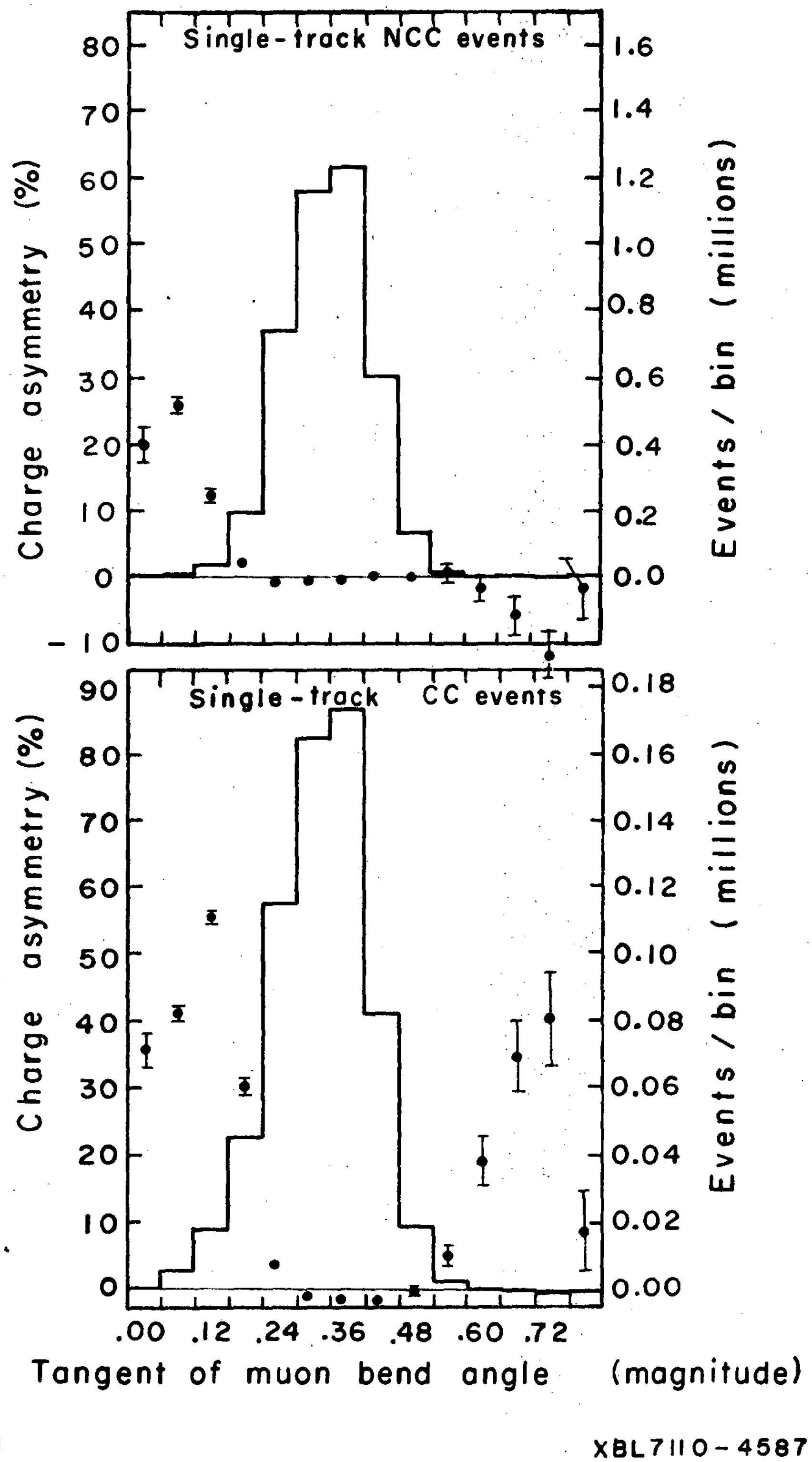

Elevation view
Up
North
N M L
T
R
S
P
A
Muon
H
Beam
Muon
Pion
Beam
Steel
Magnet
R_v
S_v
C
Vacuum tank
Steel
Magnet
Vacuum tank
Lead
wall
Pion
R_v
S_v
Muon
Beam
Pion
Beam
Muon
East
3 feet
1 meter
Plan view
North
XBL 7011-4161 A

Fig. 1



Single-track NCC events
Charge asymmetry (%)
Events / bin (millions)
80
70
60
50
40
30
20
10
0
-10
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Single-track CC events
90
80
70
60
50
40
30
20
10
0
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
.00
.12
.24
.36
.48
.60
.72
Tangent of muon bend angle (magnitude)
XBL7110-4587

Fig. 2