Scattering of High-Energy Positive and Negative Muons on Electrons*

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A counter experiment on $\mu^{\pm}e$ scattering has been performed in the muon beam at the Brookhaven AGS with particular emphasis on a possible asymmetry. Two strongly filtered beams of either sign were available, one peaked at 10.5 GeV/*c*, and the other at 5.5 GeV/*c* produced by further energy degradation in a uranium absorber. Electron energies were measured in terms of the light output produced by the cascade shower generated in a total absorption multilayer Pb scintillator counter. Two types of runs were made using the same apparatus with different event selection. In the first type all incident muons triggering the beam-defining hodoscope were counted, the effective target was distributed through the entire apparatus, and all pulses from the shower counter were measured and stored in a 400-channel pulse-height analyzer. In the second type the target volume was rather well defined, by a suitable pulse signature, to be the middle one of three water-Čerenkov counters placed in tandem in front of the shower detector. Results of the first type show that there is no asymmetry $>\pm 10\%$ in the total electromagnetic energy loss spectrum from 0.1 to 6 GeV. Results of the second type, which have less good statistics, give the absolute μ-e scattering cross section to $\pm 30\%$ with no indication of an asymmetry.

I. INTRODUCTION

A NUMBER of cosmic-ray experiments,[1–5] designed to measure the muon-electron collision cross section, have shown an anomalously large number of events in the region of several-GeV energy transfer to the electron. However, one experiment using accelerator-produced negative muons with momenta peaked at 8.5 GeV/*c* gave excellent agreement with theory and no indication of an anomaly.[6] The situation with the cosmic-ray experiments is still rather confused and complicated, and it does not yet seem to be possible to make an absolutely firm claim that the anomaly is real. Therefore no attempt is made here to give either a summary or a critical discussion of those results. We present instead in Fig. 1 a graph showing an attempt to relate the cosmic-ray data for several experiments.

The purpose of this paper is to report the results of an experiment performed at the Brookhaven AGS in a muon beam with a broad momentum spectrum peaked at 10.5 GeV/*c*. Positive and negative muons of the same momentum were used in separate data runs, and a few subsidiary runs were obtained in a negative beam peaked at 5.5 GeV. Altogether, the cosmic-ray results from our laboratory would suggest a generally larger cross section for positive than for negative muons at the larger momentum transfers, but with an apparently lower cross section for positive muons near the kinematic limit (maximum "*q*" or maximum energy transfer to the electron in the laboratory system). The present experiment was intended especially to detect the presence of an average asymmetry at a level of $\pm 10\%$ for four-momentum transfers up to 80 MeV/*c*. Because of the small ($\leq 3\%$) expected charge-asymmetric radiative corrections to the first-order quantum-electrodynamical (QED) scattering (Nikishov[7]), the experiment was undertaken in the spirit of testing for the possible existence of a new muon process rather than as a test of QED.

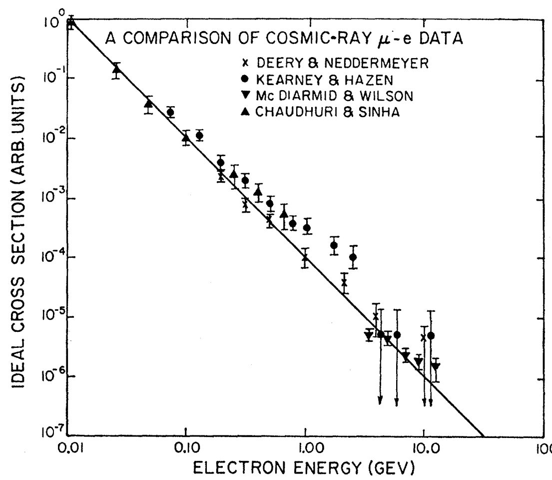

FIG. 1. Differential distributions in electron energy from various cosmic-ray experiments on μ-e scattering, shown for electron energy up to 10 GeV. The reference curve has arbitrarily been taken proportional to $1/E^2$, which would correspond to muons of infinite incident momentum; however, in each case the relation of the plotted points to the reference line is the same as the relation of the various authors's data points to their own calculated theoretical curves with regard to event energies, statistical errors, and deviations from the expected values.

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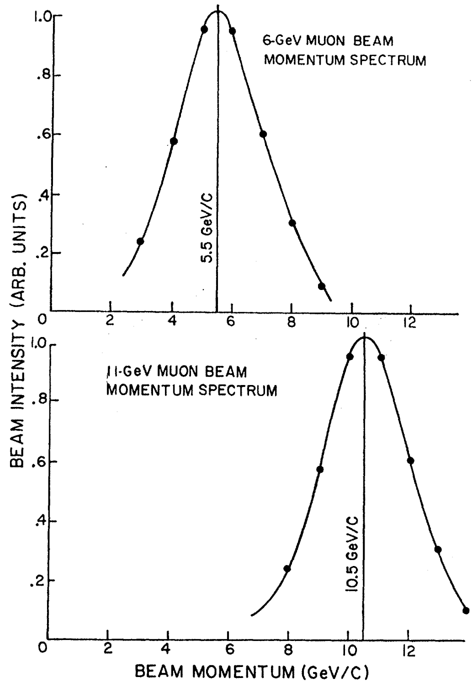

FIG. 2. Muon momentum spectra. (a) Filtered beam, as measured by the Columbia-Rochester group. (b) After traversing an additional 6-ft uranium absorber, obtained by applying a constant 5-GeV energy loss. These are the spectra actually used in the analysis of the data. Later direct measurements gave a value 5.4 instead of 5.0 GeV for the energy loss in the uranium.

II. BEAM

The muon beam at the Brookhaven AGS is produced by decay in flight of pions from an internal beryllium-wire target. After a decay flight path in vacuum of approximately 125 ft, some 10% of the pions have decayed into muons. The pions and other strongly interacting particles are then removed by nuclear interaction in a filter of beryllium and graphite, and the beam of muons which exits from the filter is expected to have a pion contamination of less than one part per million. This low level of contamination is supported by measurements made by the Columbia-Rochester group.[8] For the present purposes, such a contamination is completely negligible.

Magnetic focusing and bending of the particle paths, together with collimation by large steel blocks containing lead inserts, results in a muon beam with the momentum spectrum shown in Fig. 2(a). In part of the experiment, the beam traversed an additional 6 ft of uranium to produce the lower-energy beam of muons shown in Fig. 2(b). The spectrum in Fig. 2(a) was measured by the Columbia-Rochester group,[8] and that of Fig. 2(b) was obtained from Fig. 2(a) by use of energy-loss tables.[9] The momentum spread was so large (about 3.5 GeV/c at half-maximum, and 5.5 GeV/c at 20% maximum) that the upper energy limit of the scattered electrons was very poorly defined in the electron energy distribution.

Because the pion beam was extracted in a manner to minimize the effect of the fringing field of the ring magnet, it was possible to choose either muon sign with no appreciable change in the spectrum by reversing the current in each of the beam-transport magnets.

III. APPARATUS

A top view of the experimental apparatus is shown in Fig. 3; the muon beam goes from left to right. C1, C2, and C3 are water Čerenkov counters. S is a shower counter of lead and plastic scintillator. Beam-defining counters are placed in front of (FH1–4, FH5–8) and behind (BH6, BH8, S102) the apparatus as shown. Electrons struck in the water and in the shower counter produce large pulses in S by the generation of electromagnetic showers in the lead.

The shower counter consisted of $15\frac{1}{4}\times 11\frac{1}{2}\times 11\frac{1}{2}$-in. lead plates interleaved with 16 similar plates of plastic scintillator viewed by four 5-in. photomultiplier tubes through light pipes of clear silicone potting compound. The whole counter was contained in an aluminum box for optical, thermal, and electromagnetic isolation. The temperature of the counter was maintained constant to 0.1°C to stabilize the photomultiplier gains. The total counter was 16.7 radiation lengths thick.

The Čerenkov counters C1, C2, and C3 were used to enhance the selection of μ-e events in the water. Each was viewed by two 5-in. photomultiplier tubes with passively added outputs. Each counter measured $14\times 14 \times 9$ in. deep, large enough to eliminate edge effects of beam particles passing directly in front of the photocathode, and painted with a highly reflective Epoxy paint to maximize the light output.

Information from the shower counter was analyzed and stored by a 400-channel pulse-height analyzer. Pulses from the Čerenkov counters were progressively

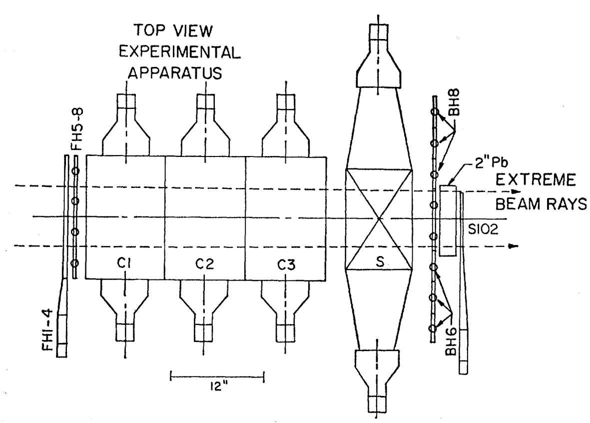

FIG. 3. Experimental apparatus.

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delayed and photographed from an oscilloscope trace in part of the experiment. A small electronic fixed-program logic and storage system was used to collect various event data and record them on punched paper tape.

The scintillation counters FH1–4 and FH5–8 were arranged in hodoscope array in front of C1. BH6 and BH8 were used in anticoincidence behind the shower counter to guard the light pipes. Counter S102 defined the beam, together with the central four hodoscope elements.

IV. EXPERIMENT

The data were of two types. In the first a minimum trigger was used which required only a muon traversal of the beam telescope, and every coincident pulse from the shower counter was digitized and stored. In this case the target is unlocalized and consists of all material in the beam path including the shower counter itself. There is a consequent degradation of the observed event energy and a corresponding broadening of the distribution, because of the varying energy losses through the back, for the fraction of events that occur deep in the shower counter. These runs have the further disadvantage that the highest-energy μ-e events that occur in the lead are very strongly dominated by a background due to bremsstrahlung of the muons. The direct pair production also contributes slightly, but equals the μ-e only in the very tail of the latter. Nevertheless, extended runs of this type were made, for several reasons: (i) There was essentially no loss of time for readout, hence better statistics for the same total operating time; (ii) the runs provided extended data on the complete energy distribution from the minimal energy loss to the highest-energy events (this was extremely valuable, because it was not possible for us to make an absolute energy calibration of the detector); (iii) they gave a check on the constancy of shower-counter performance; and (iv) somewhat independently of the validity of the energy scale, which was not determined absolutely, they provided the possibility of making a fairly accurate test of the presence of an asymmetry between μ^+-e^- and μ^--e^-, even though the μ-e was rather strongly dominated by the muon bremsstrahlung near the kinematic limit of the μ-e.

In the second type of data, selected by the Čerenkov counters, the pulses from C1, C2, and C3 were window-discriminated to favor events in which a μ-e collision occurred in the middle counter C2. In this mode of operation the apparatus could process no more than one event per beam spill; therefore a minimum pulse height was required in S in order to limit data taking to the high-energy events and avoid swamping by low-energy ones. The master event coincidence required satisfactory pulses from the beam telescope, the Čerenkov counters, the shower counter, and no pulse from the anticounters. The yes or no responses from all counters were recorded regardless of whether they participated in the trigger or not. This guarded against accidentals and upstream events. The pulse height in each Čerenkov counter was recorded on film, then later measured and written on magnetic tape for use in the final computer analysis.

V. ANALYSIS OF DATA

The relation of light output to energy has been shown to be linear for shower counters similar to ours in the range of electron energies up to several GeV.[10,11] The energy resolution for monoenergetic incoming electrons is dominated by shower fluctuations rather than photomultiplier statistics in this energy range. Heusch[10] has measured the resolution of a shower counter very similar to ours and reports a smooth variation in resolution from $\sigma = \pm 10\%$ at 1 GeV to $\pm 5\%$ at 4 GeV. His resolution curves indicated an accurately Gaussian energy distribution measured for monoenergetic incident electrons. The linearity of response presupposes adequate shower containment; our counter was sufficiently thick to contain an average of 97% of the energy of a 10-GeV shower.

A systematic error due to photomultiplier gain drift must be included in assessing the over-all precision of the measured energy spectrum. This source of uncertainty is emphasized by the steeply falling energy dependence and dominates the systematic error in the asymmetry measurement. Long-term drifts averaged 2.2% rms for all runs. Systematic correction of the spectra reduced this to 1.3% rms for the uncorrectable short-term drifts. Electronic drift was negligible by comparison with the phototube drifts.

Comparison of calculated and measured spectra indicated a nonlinear pulse-height to shower-energy relation in the shower counter later traced to space-charge saturation in the photomultiplier dynode structure for large pulses. (This counter had originally been built in Seattle as a Lucite Čerenkov counter with adiabatic light pipes. For reasons that we were never able to discover, it failed completely to function at Brookhaven, although it had passed the tests made at Seattle. It was rebuilt in the Brookhaven shop as a scintillation counter with cast pyramidal light pipes. Some loss of operating time also resulted.) The nonlinearity caused a loss of precision from about $\pm 10\%$ uncertainty to $\pm 30\%$ in the *absolute* cross-section measurement, and precluded our being able to see the radiative corrections due to high-energy photo emission as described by Gorgé *et al.*[12] The deviation from linearity was well described by a single saturation parameter E_0 in the pulse-height to shower-energy relation given by: pulse height (channel No.) $= G_0E/(1+E/E_0)$, where E is the shower energy and G_0 is a constant of

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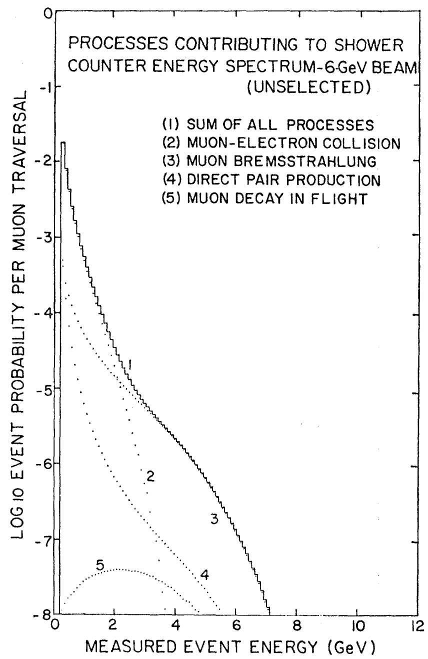
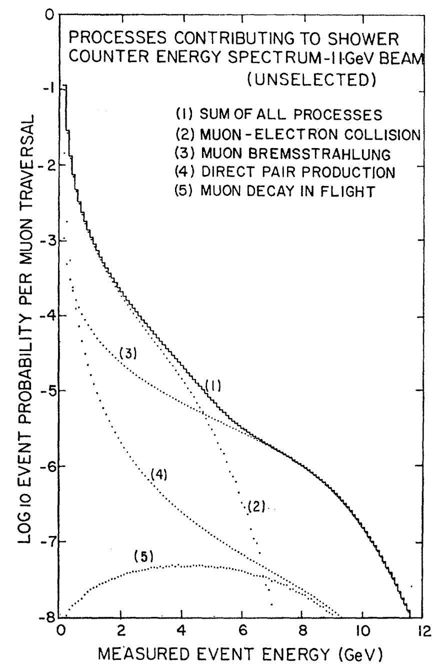
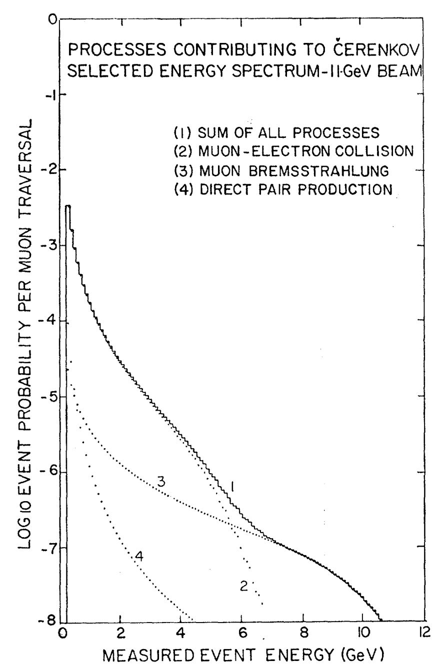


(a)



(b)



(c)

FIG. 4. Theoretical curves representing expected event probability versus measured event energy. (a) 6-GeV muons, no target selection; (b) 11-GeV muons, no target selection; and (c) 11-GeV muons, Čerenkov-selected.

proportionality. The value of E_0, determined by a consistency requirement for fitting the 6- and the 11-GeV data simultaneously, was $E_0 = 9.5$ GeV. The increase of the uncertainty in measuring the absolute cross section to 30% is attributable to the uncertainty in determining the value of E_0. Note that only the *shape* of the curve is affected by E_0. In every case there is no normalization on the ordinate, the comparison between experimental and calculated curves is absolute, and the values of G_0 and E_0 are fixed. The nonlinearity does not influence the asymmetry precision, since the effect occurs equally in both positive and negative spectra.

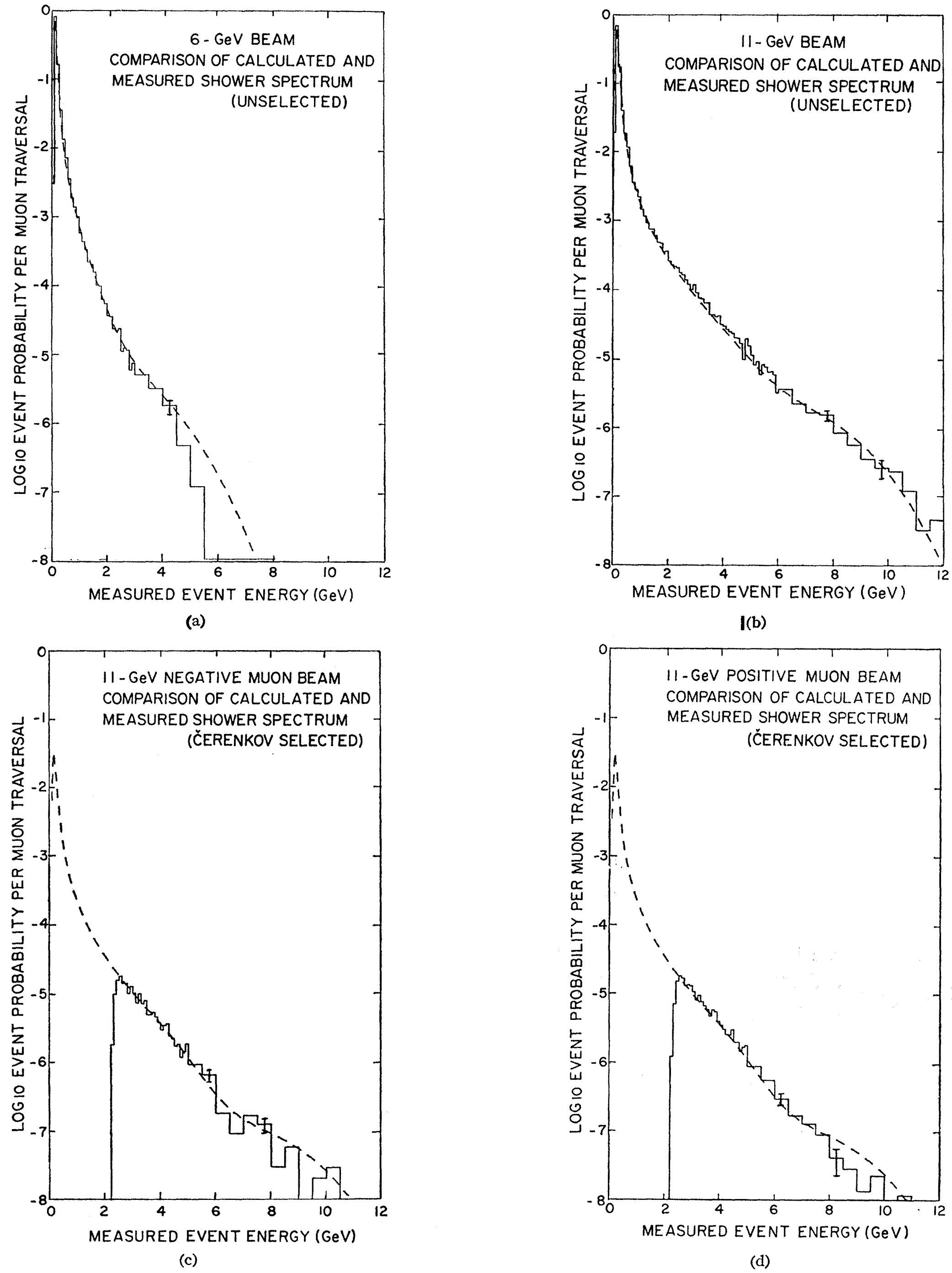


FIG. 5. Observed and calculated distributions. (a) 6-GeV μ^-, unselected. (b) 11-GeV μ^-, unselected; the corresponding curve for μ^+ is almost indistinguishable and the "asymmetry" between the two is represented in a separate graph below (Fig. 6). (c) 11-GeV μ^-, Čerenkov-selected. The rise just above 2 GeV corresponds to the lower discrimination level. (d) 11-GeV μ^+, Čerenkov-selected. The asymmetry of (c) and (d) is also represented in Fig. 6.

Calculations

The curves for the theoretically calculated shower-counter spectra are shown in Fig. 4. The contributions of the various elementary processes which contributed to the observed spectra are given separately in each case. As explained in Sec. IV, the data from runs in which the minimal trigger was used ("unselected" runs) contain contributions from material everywhere in the beam path through the apparatus plus material in the beam upstream, but the Čerenkov selected runs were

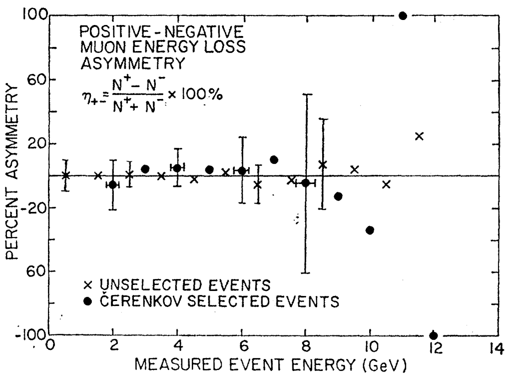


FIG. 6. Observed over-all asymmetry, shown separately for the unselected and the Čerenkov-selected data.

strongly biased to accept μ-e events from C2. For each theoretical curve the incident muon spectrum was averaged over bins of width 1 GeV. The collision probabilities, the detection probabilities, and the calculated fraction of the event energy deposited in the shower counter were folded together and integrated through the entire apparatus using numerical methods of computer analysis in order to obtain the results shown in Fig. 4. The predictions are absolutely normalized to the amount of material in the experiment and have no adjustments save the energy–pulse-height relation previously discussed.

It should be stressed that the abscissas in Fig. 4 correspond to the observed event energies in contradistinction to the true event energies, which are measured only in that fraction of events for which the entire shower is absorbed in the shower counter. The unselected data, in particular, contain a fair fraction of events for which part of the shower energy escapes the shower counter and hence represent a weighted average of true event energies ranging from the "observed" value up to the maximum possible (and uncertain, of course, by the energy resolution of the shower counter). Only 10% of the Čerenkov selected data should suffer from this effect. For this reason, the Čerenkov selected data more accurately represent an energy-dependent asymmetry, while the unselected runs offer smaller systematic and statistical errors.

VI. RESULTS

The measured energy distributions are compared with the calculated ones in Fig. 5, in terms of event probability per muon traversal and per 0.1 GeV of energy transfer. Although the results of the cross-section measurements show good agreement with the calculated values, this cannot be taken as a direct verification of theory because of the nonlinearity correction mentioned above. The agreement of the curves with the measurements should be viewed instead as a confirmation of the validity of the applied correction.

The results for the positive-negative asymmetry as determined from both the Čerenkov-selected and the unselected runs are shown in Fig. 6. For the minimum-bias runs in which every beam particle had its shower-counter pulse digitized and stored, the mean value of of $\eta\pm$ averaged over the interval 0–8 GeV is -0.9%. Such a small value of the asymmetry is probably fortuitous in view of the systematic errors, but is not inconsistent with the predictions of Nikishov.[7]

If we combine our results for the asymmetry measurement with the accurate μ-e cross section obtained by Backenstoss *et al.*[6] for negative muons, we arrive at the following conclusions: (1) To an accuracy of $\pm 10\%$ there is no cross-section asymmetry observed between positive and negative muons scattered by electrons in the energy-transfer range 100 MeV to 6 GeV; (2) the cross section is well described for both particles by the first-order scattering diagram (Bhabha formula) corrected for hard-photon radiation as described by Gorgé *et al.*,[12] although our results alone are insufficient to test the latter. The results are in apparent conflict with the cosmic-ray measurements.

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