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INCLUSIVE ANOMALOUS MUON PRODUCTION IN e^+e^- ANNIHILATION*

G.J. Feldman, F. Bulos, D. Lüke,† G.S. Abrams, M.S. Alam, A.M. Boyarski, M. Breidenbach, J. Dorfan, C.E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F.B. Heile, J.A. Jaros, J.A. Kadyk, R.R. Larsen, A.M. Litke, V. Lüth, R.J. Madaras, C.C. Morehouse, H.K. Nguyen,†† J.M. Paterson, M.L. Perl, I. Peruzzi,§ M. Piccolo,§ F.M. Pierre,§§ T.P. Pun, P. Rapidis, B. Richter, B. Sadoulet, R.F. Schwitters, W. Tanenbaum, G.H. Trilling, F. Vannucci,‡ J.S. Whitaker, and J.E. Wiss

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

and

Lawrence Berkeley Laboratory and Department of Physics
University of California, Berkeley, California 94720

ABSTRACT

We present measurements of inclusive anomalous muon production in e^+e^- annihilations in three energy ranges. In all three ranges we observe a large anomalous muon production rate in two-prong events which is compatible with the expected decays of pairs of heavy leptons. In the highest energy range there is also appreciable anomalous muon production in multiprong events which, due to its magnitude and momentum dependence, must come in part from a source other than a heavy lepton.

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*Work supported by the Energy Research and Development Administration.
†Fellow of Deutsche Forschungsgemeinschaft.
††Permanent address: LPNHE, Université Paris VI, Paris, France.
§Permanent address: Laboratori Nazionali, Frascati, Rome, Italy.
§§Permanent address: Centre d'Etudes Nucléaires de Saclay, France.
‡Permanent address: Institut de Physique Nucléaire, Orsay, France.

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In previous Letters we presented evidence suggesting that a new lepton[1,2] and charmed mesons[3] are produced in e^+e^- annihilations at center of mass energies (E_{cm}) above 4 GeV. By measuring inclusive muon production we can investigate the leptonic and semileptonic decays of these and possibly other new weakly decaying particles.[4]

The data presented here come from the SLAC-LBL magnetic detector[5] at SPEAR and, in particular, from a muon detector (the muon tower) which is located above the main detector. A schematic drawing of the muon detection system is shown in Fig. 1. To reach the first layer of muon detection spark chambers (level one) a particle must pass through a 24 gm/cm^2 thick aluminum coil, a 42 gm/cm^2 thick lead-scintillator sandwich shower counter, and a 160 gm/cm^2 thick iron magnetic flux return. To reach the second or third layers of spark chambers (level two or three) a particle must, in addition, pass through one or two 222 gm/cm^2 thick slabs of barite-loaded concrete. Taking the average angle of incidence into account, the total material before levels two and three is equivalent to 65 and 92 cm of iron, respectively. Thus the minimum average momentum required for a muon to reach level two is 910 MeV/c. The solid angle subtended by level two is 1.1 sr.

Tracks are momentum analyzed by the cylindrical spark chambers and projected into the muon tower. For the purpose of this Letter a candidate is a particle which because of its direction and momentum would be detected by a muon spark chamber at level two or three if it were a muon. A muon is a candidate which is detected in every muon spark chamber through which it is projected within three standard deviations of the expected multiple coulomb scattering. Anomalous muons are those remaining after background muons from well known sources have been subtracted.

Two important sources of background muons are hadron penetration and decay.

We calculate the former by doing Monte Carlo simulations with the High Energy Nucleon-meson Transport Code HETC[6] and the latter analytically. In these calculations the candidates are assumed to be 80% π's and 20% K's in rough agreement with measurements.[7]

There are two experimental checks to these calculations. First, we can calculate the number of muons expected in multiprong ψ decays, where we expect no anomalous muon production. From a sample of ψ decays containing 1879 candidates we calculate that there should be 52.7 muons from hadron penetration or decay and we observe 57 muons. Second, we can calculate the number of candidates at level three which are detected in spark chambers at levels one and two but are not detected at level three. These events are almost entirely due to hadrons which penetrate or decay to level two. From high energy multiprong data containing 3491 candidates at level three, we calculate that there should be 161 events of this type and we observe 156 events. From these checks and our estimates of possible systematic errors, we consider the penetration and decay calculations to be accurate to 25%.

Other than π's and K's, ψ's are the only particles whose decays could conceivably contribute a substantial number of muons. We have looked for inclusive ψ production by plotting the invariant mass distribution of pairs of particles which include a muon. There is no enhancement at the ψ mass implying that the number of muons from ψ decay is negligible for these data.

The other sources of background muons we have considered are radiative μ pair production, $e^+e^- \rightarrow \mu^+\mu^-\gamma$[8] and $\mu^+\mu^-\gamma\gamma$[9], and the two-photon process $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$.[10] These reactions primarily contribute muons to events in which only two charged particles are detected. To remove most of the muons from these reactions we require two-prong events to be acoplanar with the incident beams by at least 20° and for the square of the missing mass (m_x^2) recoiling against the two observed prongs to be greater than 1.5 $(\mathrm{GeV}/c^2)^2$. As a check on our calculation of radiative μ pair production and our ability to measure muon production rates we have also examined two prong events which are acoplanar by at least 20°, but which have $m_x^2 < 1.5$ $(\mathrm{GeV}/c^2)^2$. Muons found in these events should result almost entirely from radiative μ pair production. In the E_{cm} region 3.9 to 4.8 GeV we expect 37.9 events and we observe 41 events, and in the E_{cm} region 5.8 to 7.8 GeV we expect 55.8 events and we observe 53 events. We consider the calculation of backgrounds from leptonic sources to be accurate to 20%.

In events with three or more observed charged prongs, we eliminated pairs of oppositely charged particles the cosine of whose opening angle was greater than 0.99 because these pairs were most likely from photon conversions in the 0.052 radiation lengths of material in the vicinity of the beam pipe. In addition, all events containing a muon were examined individually and obvious examples of μ pair production with photon conversions were eliminated.

The results for anomalous muon production are given in Table I. The cross sections given are corrected for all geometrical, detection, and triggering efficiencies, but not for the average minimum momentum required to be detected in the tower (910 MeV/c) or, for two prongs, the coplanarity and missing mass cuts.

In the two-prong case there is a large anomalous muon signal in all three energy regions.[11] Theoretically, one expects that about 87% of the time the decay products of a heavy lepton will contain only one charged particle.[12] Thus muons from the decay of a pair of heavy leptons should appear primarily in two-prong events. The expected two prong cross sections for a heavy lepton with a V-A decay, a branching fraction to $\mu\nu\bar{\nu}$ of 0.17 and a mass between 1.6 and 2.0 GeV/c^2, are given in Table I.[13] In all three energy ranges the measured anomalous muon cross sections in two-prong events are consistent with coming almost entirely from heavy lepton pairs.

The momentum spectrum for the anomalous muons in two prong events in the highest E_{cm} range is shown in Fig. 2a along with the spectrum expected from a heavy lepton in the mass range 1.6 to 2.0 GeV/c^2 and other parameters as given above. The two spectra are in reasonable agreement.

In the multiprong data there is a suggestion of anomalous muon production in the two lower energy ranges, but it is not conclusive. In the highest energy range the signal is 5 ± 2 times that expected from heavy lepton pairs with branching fractions as given above. Furthermore, the muon momentum spectrum from heavy lepton pairs should be independent of the event multiplicity, whereas the spectrum observed in multiprong events, shown in Fig. 2b, is much steeper than that observed for two-prong events or expected from heavy lepton decays.

Figure 3 shows the anomalous cross section and the anomalous muon to candidate ratio in the highest E_{cm} range. In both cases the contrast between two prongs and more than two prongs is striking.

In summary we have observed a large rate of anomalous muon production in two-prong events consistent with what is expected from heavy lepton decays. In the 5.8 to 7.8 GeV energy range we have also observed an anomalous muon production rate in multiprong events which is several times that expected from heavy lepton decays and which decreases with muon momentum at a much faster rate than expected from such decays. Thus, these muons must come in part from another source, presumably the weak decays of new hadrons.

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11. In 59 of the two-prong muon events with $5.8 \lesssim E_{cm} \lesssim 7.8$ GeV, the second prong can be identified as a μ, e, or hadron using the criteria of Ref. 1. After correcting for all backgrounds and misidentifications there are 6.8 ± 6.3 $\mu\mu$ events, 14.2 ± 4.8 μe events, and 19.5 ± 6.5 μ hadron events. From the data of Ref. 2, we expect $6.2^{+5.1}_{-2.0}$ μe events.
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13. In Ref. 2 if the observed anomalous $e\mu$ events are interpreted as coming from a sequential heavy lepton with a V-A decay, then the branching fraction to $\mu\nu\bar{\nu}$ is $0.17^{+0.06}_{-0.03}$ and the mass lies between 1.6 and 2.0 GeV/c^2.

TABLE I. Anomalous muon production results.

E_{cm} range (GeV)	3.9 to 4.3	4.3 to 4.8	5.8 to 7.8
Average E_{cm} (GeV)	4.05	4.4	6.9
Integrated luminosity (pb^{-1})	2.44	2.35	16.2
<u>Two-prong events</u>			
Candidates[a]	181	224	902
Muons	24	29	177
Radiative μ pairs	2.3	2.2	17
eeμμ events	1.4	1.8	29
Hadron penetration or decay	5.0	6.4	28
Anomalous muons	15.3 ± 5.1	18.6 ± 5.7	103 ± 18
Anomalous cross section (pb)	194 ± 71	253 ± 86	212 ± 49
Expected heavy lepton contribution (pb)[b]	252 to 57	290 to 197	195 to 218
<u>Three-or-more-prong events</u>			
Candidates	1217	1392	10738
Muons	47	52	571
Hadron penetration or decay	33.2	38.4	325
Anomalous muons	13.8 ± 10.8	13.6 ± 12.0	246 ± 85
Anomalous cross section (pb)	103 ± 82	105 ± 94	248 ± 93
Expected heavy lepton contribution (pb)[b]	51 to 10	58 to 36	47 to 46

a) Events with both prongs identified as electrons are excluded.
b) For a mass range from 1.6 to 2.0 GeV/c^2. See text for other parameters.

FIGURE CAPTIONS

1. The magnetic detector as seen looking in the direction of the incident beams. Proportional chambers around the beam pipe and trigger counters around the beam pipe and just inside the coil are not shown.

2. Differential cross section for anomalous muon production versus momentum for a) two-prong events and b) multiprong events in the E_{cm} range 5.8 to 7.8 GeV. The solid curve represents the expected cross section from the decays of heavy leptons with parameters as specified in the text.

3. a) Anomalous muon production cross section and b) ratio of anomalous muons to candidates versus the number of observed charged prongs in the E_{cm} range 5.8 to 7.8 GeV. Note that the two-prong cross section is not corrected for a coplanarity cut and is thus artificially suppressed relative to multiprong cross sections. In calculating the two-prong μ fraction, the number of candidates has been corrected to eliminate leptonic reactions.

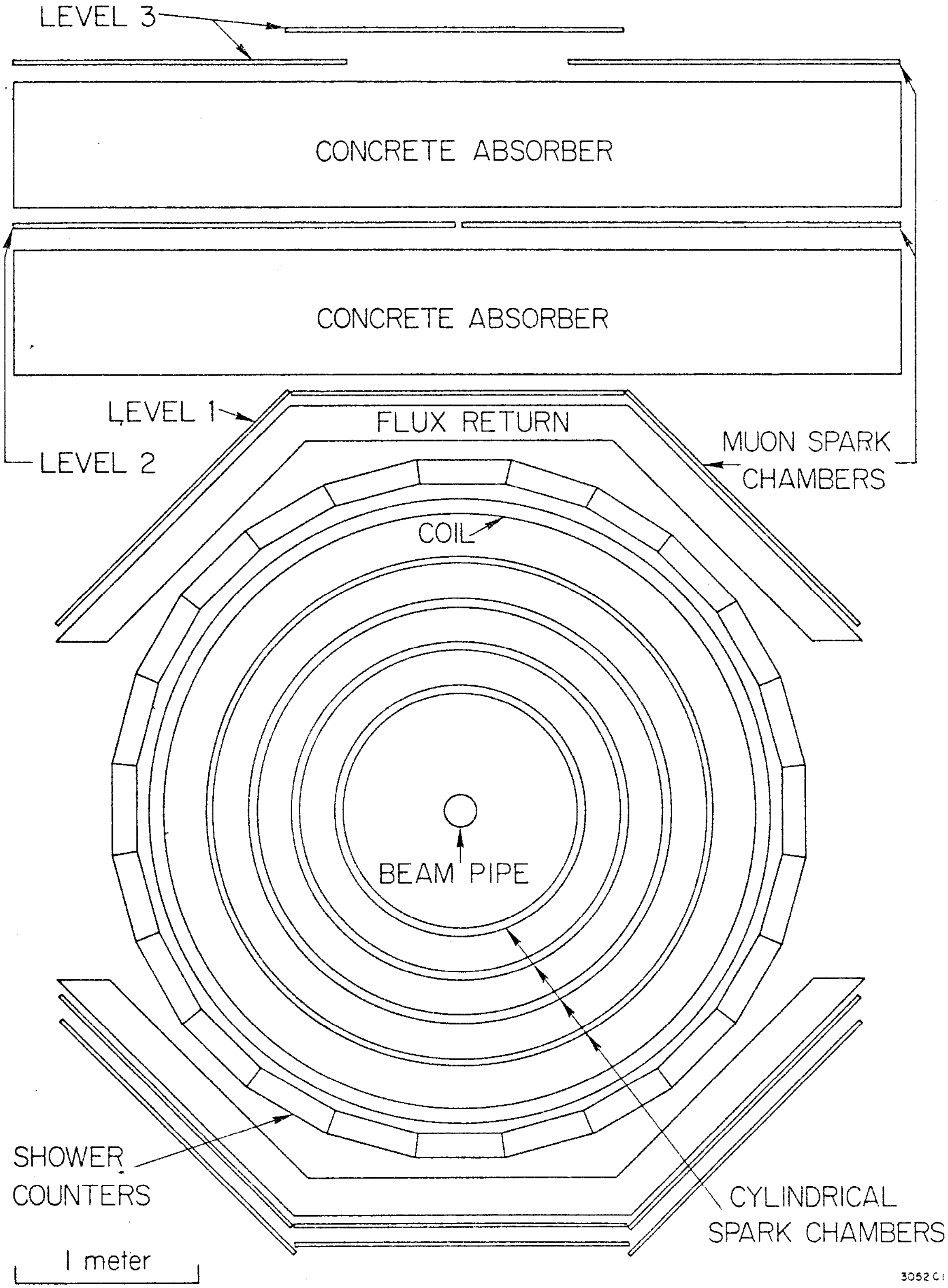

LEVEL 3
CONCRETE ABSORBER
CONCRETE ABSORBER
LEVEL 1
FLUX RETURN
LEVEL 2
MUON SPARK
CHAMBERS
COIL
BEAM PIPE
SHOWER
COUNTERS
CYLINDRICAL
SPARK CHAMBERS
1 meter
3052C1

Fig. 1

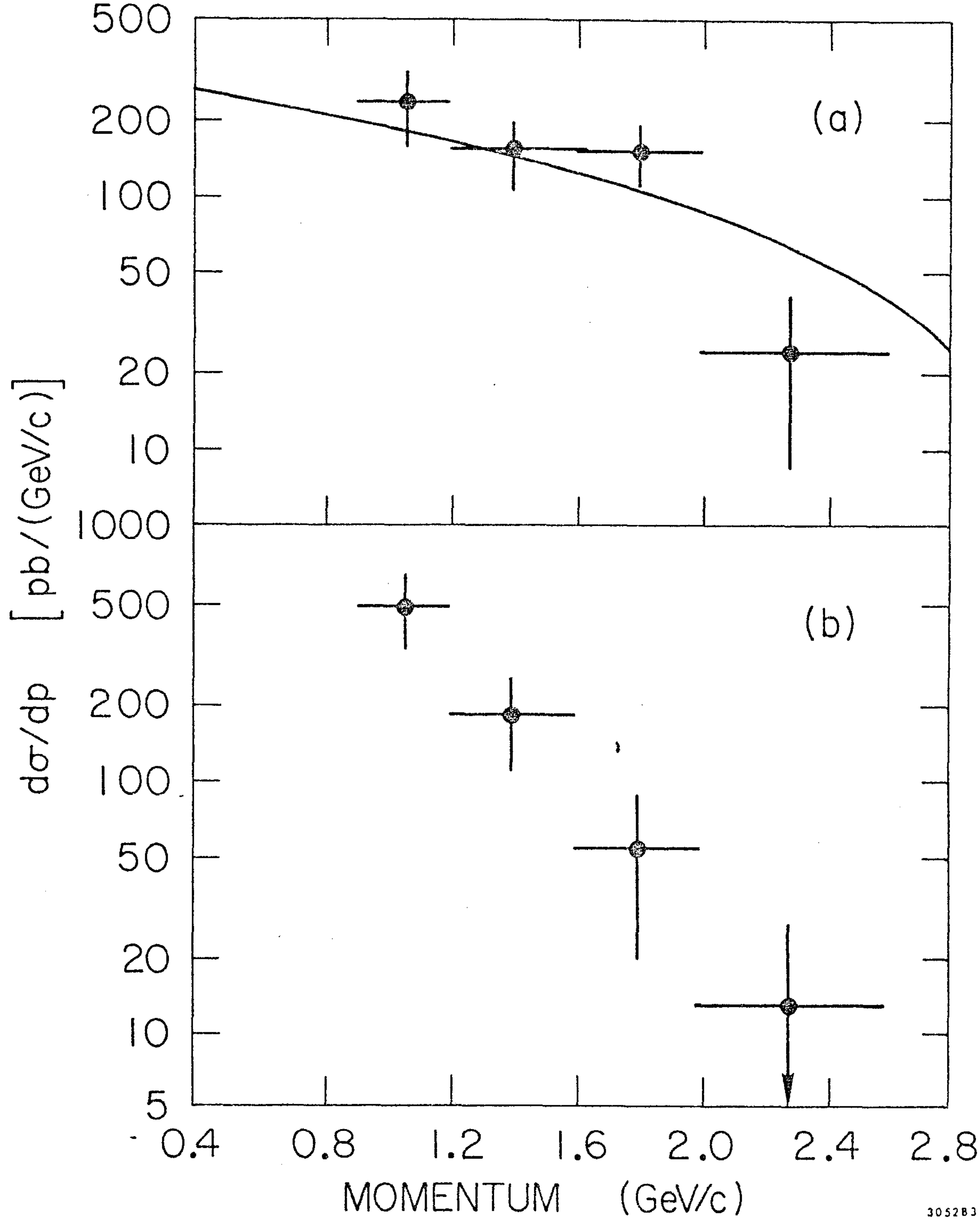
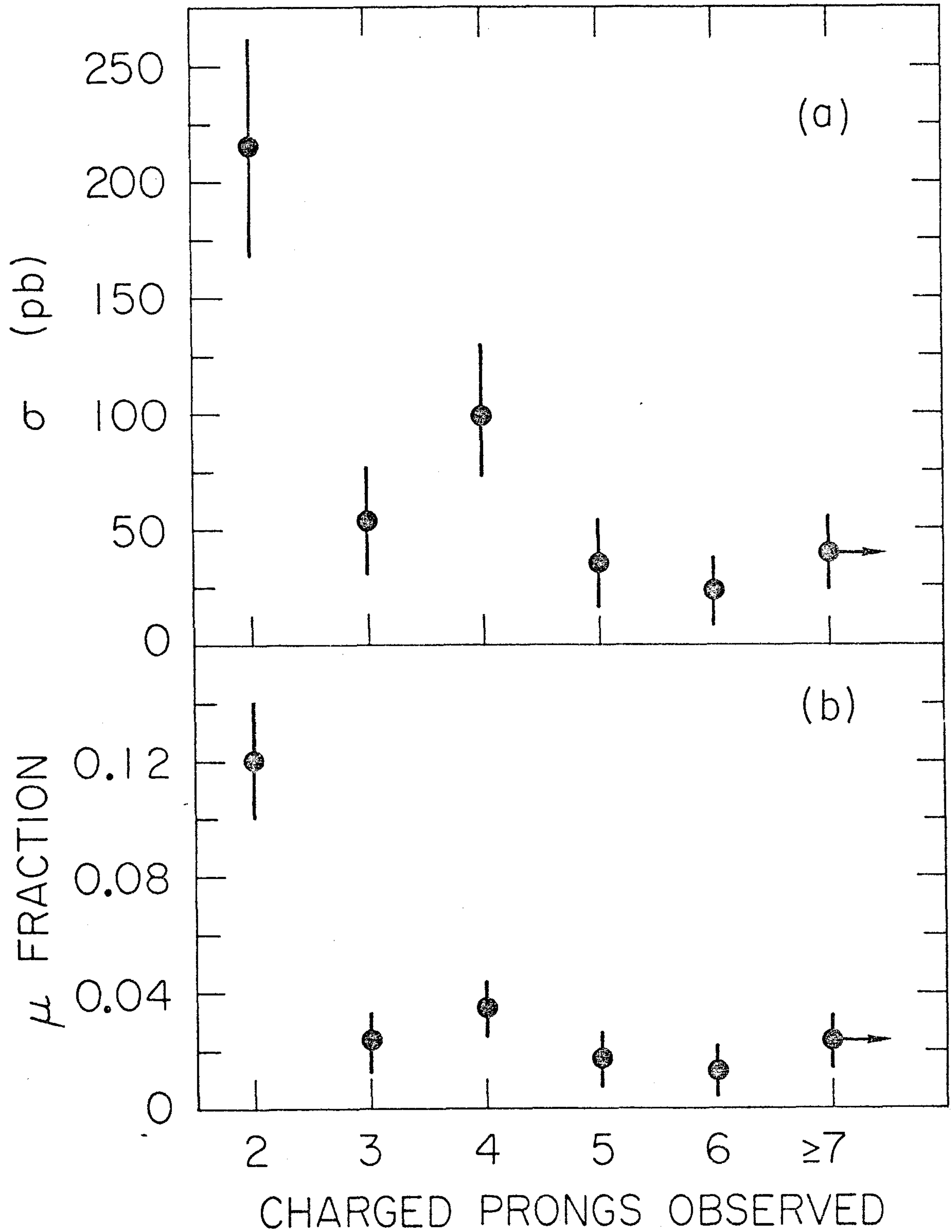

500
200
100
50
20
10
1000
500
200
100
50
20
10
5
(a)
(b)
dσ/dp [pb/(GeV/c)]
0.4
0.8
1.2
1.6
2.0
2.4
2.8
MOMENTUM (GeV/c)
305283

Fig. 2



250
200
150
100
50
0
σ (pb)
(a)
0.12
0.08
0.04
0
μ FRACTION
(b)
2
3
4
5
6
≥7
CHARGED PRONGS OBSERVED
3052B2

Fig. 3