Fermi National Accelerator Laboratory

FERMILAB-Pub-78/31-THY
March 1978

How to Extract Heavy Quark and Heavy Lepton Signals in Neutrino-Induced Dilepton Events[†]

CARL H. ALBRIGHT[*]
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

J. SMITH
Institute for Theoretical Physics
State University of New York at Stony Brook
Stony Brook, New York 11794

ABSTRACT

Several key tests for neutrino-produced dilepton events are presented which allow one to identify rather clearly new signals arising from heavy quarks or heavy leptons in the presence of a substantial charm background.

---

[*]Permanent address: Department of Physics, Northern Illinois University, DeKalb, Illinois 60115.

[†]Work supported in part by the National Science Foundation under Grant Nos. PHY77-07864 and PHY76-15328 and by the Department of Energy.

Operated by Universities Research Association Inc. under contract with the Energy Research and Development Administration

When neutrino-induced dilepton events were first discovered[1] three years ago, several possible sources were advanced to explain these events: trident production in the Coulomb field of the nucleus,[2] W-boson production and decay into leptons,[3] production and semileptonic decay of charm,[4] and M^0 heavy lepton production and decay.[5] The first two explanations were easily eliminated on the basis of distributions and rates, and subsequent analysis with much greater statistics by several experimental groups[6] now demonstrates rather clearly that the bulk of the $\mu^-\mu^+$ and μ^-e^+ events are due to the charm reaction

$$\nu_\mu + N \rightarrow \mu^- + C + x$$
$$\hookrightarrow S + \nu_{\mu(e)} + \mu^+(e^+) \quad . \tag{1}$$

This short communication addresses the possibility of searching for and identifying additional signals in the data at the level of 10% of the charm signal. Two recent developments make such a search attractive. The discovery[7] of the $\Upsilon(9.4)$, the $\Upsilon'(10.0)$ and probably Υ'' in p-N collisions is widely interpreted[8] as evidence for new hidden flavors such as b(Q = -1/3) or t(Q = 2/3) quarks. If such new heavy quarks exist, it is important to determine whether they can be produced directly in $\bar{\nu}$ or ν reactions off the valence u or d quarks, respectively:[9]

$$\bar{\nu}_\mu + u \rightarrow \mu^+ + b + x$$
$$\hookrightarrow u + \mu^- + \bar{\nu}_\mu \tag{2a}$$

$$\nu_\mu + d \rightarrow \mu^- + t + x$$
$$\hookrightarrow d + \nu_\mu + \mu^+ \quad . \tag{2b}$$

On the other hand, $\bar{b}$ or $\bar{t}$ production in ν or $\bar{\nu}$ reactions may occur off the $\bar{u}$ or $\bar{d}$ sea partons, respectively. Secondly, some data have recently been interpreted[10] to suggest production and decay of an M^0 heavy lepton with mass around 2 GeV:

$$\nu_\mu + N \to M^0 + X, \quad M^0 \to \mu^- + \nu_{e(\mu)} + e^+(\mu^+) \quad . \tag{3}$$

We show here how to separate new signals from charm and how to distinguish new flavor production from heavy lepton production.

We first review the tests that have been used to identify charm rather than M^0's as the dominant signal in dilepton reactions.

(A) E_{μ^-} vs. E_{μ^+} Scatter Plots

In the case of the charm reaction (1), the μ^+ energy tends to be small, while for the M^0 process (3) the μ^- and μ^+ energies are more nearly comparable on the average.[5] Pais and Treiman[11] have neatly summarized this point for the heavy lepton process by bounding the ratio of the average energies in the range $0.5 \lesssim \langle E_{\mu^+} \rangle / \langle E_{\mu^-} \rangle \lesssim 2.0$, independent of the form of interaction. For antineutrino production, the situation is just reversed for the μ^- and μ^+ energies.

(B) Invariant Dimuon Mass: $M_{\mu\mu}$

Since the two muons arise from the same source in the M^0 process, the dimuon invariant mass must be bounded from above by the mass of the heavy lepton. In the case of the charm reaction, prompt and decay muons arise from different vertices, i.e. the lepton sources are nonlocal, and the dimuon invariant mass can have a long tail extending upward to 10 GeV/c^2 or thereabouts.

(C) Azimuthal Opening Angle: $\phi_{\mu\mu}$

For reaction (1), the μ^+ from the charm decay tends to follow the hadron jet direction with the result that the two muons favor a back-to-back alignment in the plane perpendicular to the beam direction. For the heavy lepton process, on the other hand, the M^0 is produced away from the beam direction, and the two muons from the decay can be emitted with relatively small azimuthal angles projected onto the plane normal to the beam direction. In fact, the $\phi_{\mu\mu}$ distribution peaks at small opening angles for this process.

Enough statistics have been accumulated from the neutrino counter and bubble chamber experiments to indicate convincingly that all three tests favor the charm interpretation in the $\mu^-\mu^+$ and μ^-e^+ dilepton event samples.[6] If one asks whether any evidence exists for still more massive quark flavors or heavy leptons, the above tests are of little use since one must isolate an additional ($\lesssim$ 10%) signal above the charm background. To illustrate this point, we show in Fig. 2 scatter plots of E_{μ^+} vs. E_{μ^-} for the production of charmed quarks, bottom flavor quarks, and heavy leptons by neutrinos.[F1] While the latter two graphs are substantially different from the charm predictions, when statistically suppressed and plotted on top of the charm signal one sees that it would be very difficult to identify a new signal over and above charm with any degree of certainty.

It is possible to single out tests, however, for which the charm background is negligibly small. Among the most sensitive we have found are the following:

(D) Momentum Transverse to the Production Plane:[F2] p_T

To the extent that the charm particle is produced along the hadron jet direction, the secondary μ^+ can only carry a limited amount of momentum out of the production plane,[12] i.e. $p_T < 0.5\, M_c c$, where M_c is the mass of the charmed quark (or hadron). For the parameters chosen,[F3] we find $p_T \lesssim 0.75$ GeV/c. In the case of a heavier quark such as the bottom (or top) quark associated with the $\Upsilon(9.4)$, the kinematically-allowed region for p_T is considerably larger, $p_T \lesssim 2.4$ GeV/c. In the heavy lepton process (3), the μ^+ can carry off a substantial momentum transverse to the production plane defined by the outgoing μ^-. Here we find $p_T \lesssim 2.0$ GeV/c. Curves for these three cases are given in Fig. 2.

(E) $\phi_{\mu\mu}$ vs. p_T Scatter Plot

If a significant number of events are found for which $p_T \gtrsim 0.8$ GeV/c so that a new signal beyond charm is apparent, one can attempt to distinguish a new quark flavor from a heavy lepton by plotting the azimuthal opening angle $\phi_{\mu\mu}$ vs. p_T as shown in Fig. 3. The $\phi_{\mu\mu}$ angle peaks near 180° for heavy quark decay while it peaks near 0° for a heavy lepton reaction. By focussing on these events for which $p_T \gtrsim 0.8$ GeV/c, one can then try to separate a heavy quark signal from a heavy lepton signal. From Fig. 3 we see that $\langle\phi_{\mu\mu}\rangle$ ($p_T > 0.8$ GeV/c) $\approx 110^\circ$ for the heavy quark reaction (2) and $\approx 45^\circ$ for the heavy lepton reaction (3).

(F) $M_{\mu\mu}$ vs. p_T Scatter Plot

As an additional check of the separation of heavy quark and heavy lepton signals, one can plot the dimuon invariant mass against the p_T variable. As noted previously in (B), $M_{\mu\mu}$ is bounded from above by the mass of the heavy lepton, while no bound exists for the heavy quark process. The results are plotted in Fig. 4 where the differences for $p_T > 0.8$ GeV/c are quite apparent.

In summary, we have pointed out several tests which can easily be employed to separate heavy quark and neutral heavy lepton signals (if any) from each other and from the charm background in neutrino-produced dimuon events. One should first check whether any events are observed where the secondary muon has $p_T \gtrsim 0.8$ GeV/c out of the production plane. If a significant number of such events exist, one can then attempt to separate a heavy quark from heavy lepton signals by constructing $\phi_{\mu\mu}$ vs. p_T and $M_{\mu\mu}$ vs. p_T scatter plots. For $p_T \gtrsim 0.8$ GeV/c, a peaking of $\phi_{\mu\mu}$ at large (small) angles and an unbounded (bounded) $M_{\mu\mu}$ distributions suggest new quark (heavy lepton) production.

All our figures have been drawn for neutrino beam reactions. With antineutrino beams, the resulting graphs in Figs. 2-4 are quite similar and need not be repeated here. We note, however, that with the neutrino and antineutrino fluxes properly taken into account, one would expect b quark production in antineutrino beams to greatly exceed $\bar{b}$ production in neutrino beams since the production can take place off valence quarks in the former. For t quark production, just the opposite will be true. With heavy leptons, on the other hand, the relative rates in neutrino and antineutrino beams should differ by less than a factor of three after appropriate flux corrections are made. We believe that the tests presented here are considerably more sensitive to new quark or lepton production than the corresponding tests in single muon reactions.

We wish to acknowledge C.-H. Lai for several conversations concerning his work on charm production by neutrinos and thank C. Baltay and M.J. Murtagh for discussions of their data and the feasibility of making the tests suggested here.

FOOTNOTES

[F1]Here and in the following we choose masses of the charm and bottom quarks to be 1.6 GeV/c^2 and 4.75 GeV/c^2, respectively, and take 2 GeV/c^2 for the mass of the M^0 heavy lepton. The slow rescaling variable ξ is used for the heavy quarks with a flat fragmentation function for charm and one peaked at z=0.8 for the bottom flavor. The distributions have been folded with the FNAL quadrupole triplet neutrino spectrum and a 4 GeV cut made on the muon energies, but our results (as opposed to the actual rates) are not very sensitive to the type of spectrum used.

[F2]The transverse momentum variable $p_\perp$ relative to the hadron jet direction can also be used, but we find that p_T relative to the production plane is a better test and also easier to measure experimentally.

[F3]If one takes into account the limited transverse momentum of the charmed hadron out of the hadron jet direction, the range in p_T is extended somewhat higher. The choice of a flat fragmentation function for charm rather than an e^{-3z} form which better describes the experimental results[13] tends to compensate for this smearing effect. Folding in an exp $(-4p_\perp^{\;2})$ distribution for the outgoing charmed particle relative to the hadron jet axis, we find less than 4% (0.5%) of the charm events have a p_T >0.8 GeV/c if a 4 GeV (0.3 GeV) cut is made on the lepton energy. The smaller numbers are applicable for bubble chamber experiments. In any case, one can draw a smooth rapidly falling curve through the low p_T data which is mostly charm and observe whether a second curve having a much longer tail and representing a new signal is required to describe the data well.

REFERENCES

[1] A. Benvenuti, et al., Phys. Rev. Lett. 34, 419 (1975); B.C. Barish, et al., Colloq. Inst. CNRS 245, 131 (1975).

[2] R.W. Brown, R.H. Hobbs, J. Smith, and N. Stanko, Phys. Rev. D6, 3273 (1972); K. Fujikawa, Ann. Phys. (NY) 68, 102 (1971); 75, 491 (1973).

[3] R.W. Brown and J. Smith, Phys. Rev. D3, 207 (1971); R.W. Brown, R.H. Hobbs, and J. Smith, Phys. Rev. D4, 794 (1971).

[4] M.K. Gaillard, B.W. Lee, and J.L. Rosner, Rev. Mod. Phys. 47, 277 (1975); L.M. Seghal and P. M. Zerwas, Phys. Rev. Lett. 36, 399 (1976); V. Barger and R.J.N. Phillips, Phys. Rev. Lett. 36, 1226 (1976).

[5] L.N. Chang, E. Derman, and J.N. Ng, Phys. Rev. Lett. 35, 6 (1975) and Phys. Rev. D12, 3539 (1975); C.H. Albright, Phys. Rev. D12, 1319 (1975).

[6] A. Benvenuti, et al., Phys. Rev. Lett. 35, 1203 (1975); ibid. 1249 (1975); J. Blietschau, et al., Phys. Lett. 60B, 207 (1976); P. Bosetti, et al., Phys. Rev. Lett. 38, 1248 (1977); C. Baltay, et al., Phys. Rev. Lett. 39, 62 (1977); B. C. Barish, et al., Phys. Rev. Lett. 39, 981 (1977); M. Holder, et al., Phys. Lett. 69B, 377 (1977); H.C. Ballagh, et al., Phys. Rev. Lett. 39, 1650 (1977).

[7] S.W. Herb, et al., Phys. Rev. Lett. 39, 252 (1977); W.R. Innes, et al.. ibid. 1240, 1640(E), (1977).

[8] Previous references can be traced from the recent papers by E. Eichten and K. Gottfried, Phys. Lett. 66B, 286 (1977); C.Quigg and J.L. Rosner, Phys. Lett. 71B, 153 (1977); D.B. Lichtenberg, J.G. Wills, and J.T. Kiehl, Phys. Rev. Lett. 39, 1592 (1977); T. Hagiwara, Y. Kazama, and E. Takasugi, Phys. Rev. Lett. 40, 76 (1978).

[9] C.H. Albright, R.E. Shrock, and J. Smith, Phys. Rev. D (to be published).

[10] D.S. Barbanov, et al., Phys. Lett. 70B, 269 (1977); H. Faissner, et al., Proc. Int. Neutrino Conference, Elbrus (1977), to be published; E. Radermacher, Proceedings of the Ben Lee Memorial International Conference on Parity Nonconservation, Weak Neutral Currents and Gauge Theories, Fermilab (1977), to be published.

[11] A. Pais and S.B. Treiman, Phys. Rev. Lett. 35, 1206 (1975).

[12] L.M. Sehgal and P.M. Zerwas, Phys. Rev. Lett. 36, 399 (1976).

[13] C. Baltay and N. Samios, private communication.

FIGURE CAPTIONS

Fig. 1: Scatter plots of E_μ^+ vs. E_μ^- for (a) the charm process in (1), (b) heavy bottom quark process $\nu_\mu + \bar{u} \to \mu^- + \bar{b}$, $\bar{b} \to \bar{u} + \nu_\mu + \mu^+$, and (c) heavy lepton process (3). The numbers in each bin indicate the relative number of events out of 1000 which occur in that bin and survive the 4 GeV muon energy cuts.

Fig. 2: Histograms for the p_T variable for (a) charm, (b) bottom quark, and (c) M^0 reactions.

Fig. 3: Scatter plots of $\phi_{\mu\mu}$ vs. p_T for (a) bottom quark and (b) M^0 production.

Fig. 4: Scatter plots of $M_{\mu\mu}$ vs. p_T for (a) bottom quark and (b) M^0 production.

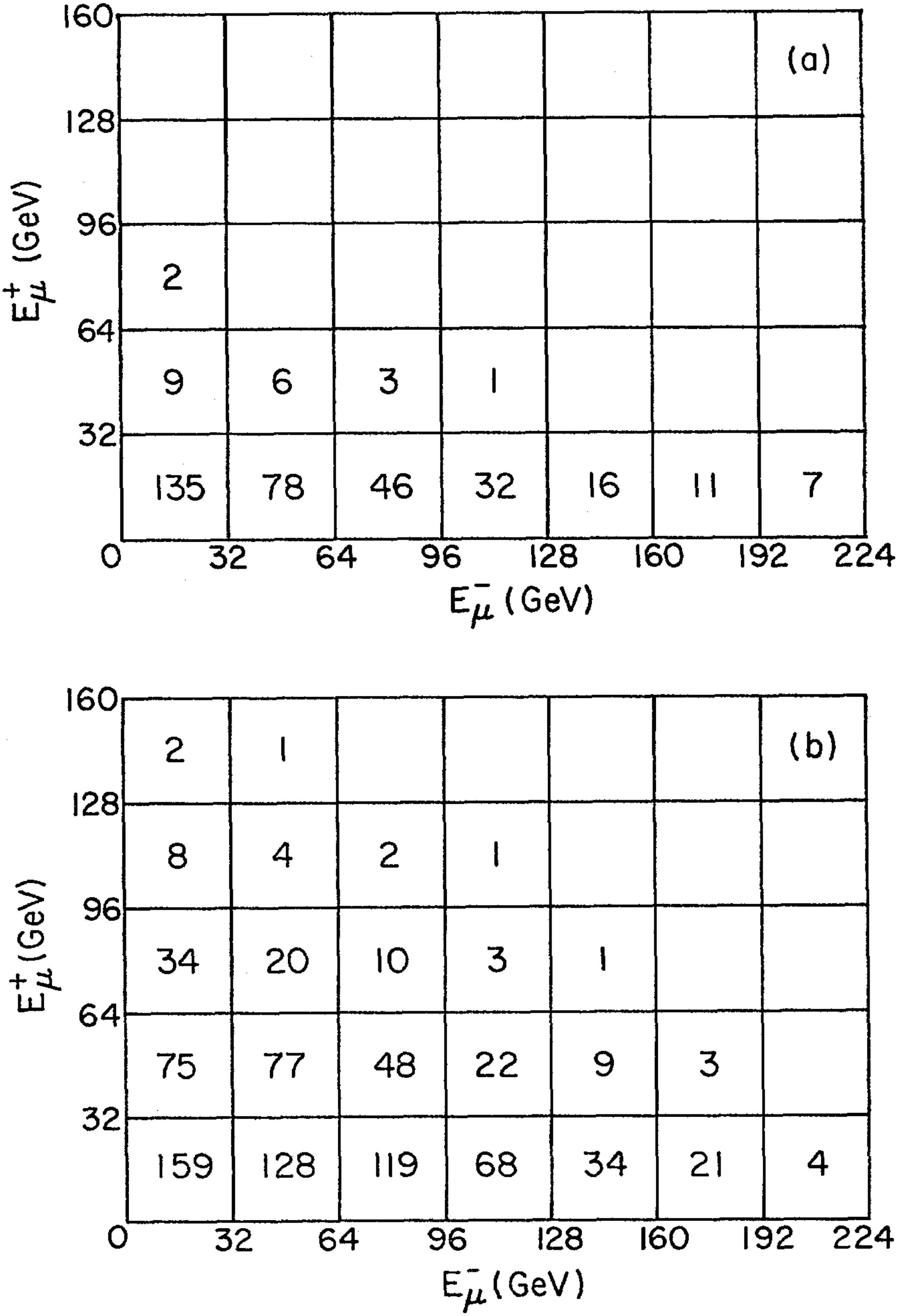
(a)
E_μ^+ (GeV)
E_μ^- (GeV)
160
128
96
64
32
0
32
64
96
128
160
192
224
2
9 6 3 1
135 78 46 32 16 11 7
(b)
E_μ^+ (GeV)
E_μ^- (GeV)
160
128
96
64
32
0
32
64
96
128
160
192
224
2 1
8 4 2 1
34 20 10 3 1
75 77 48 22 9 3
159 128 119 68 34 21 4

Fig. 1

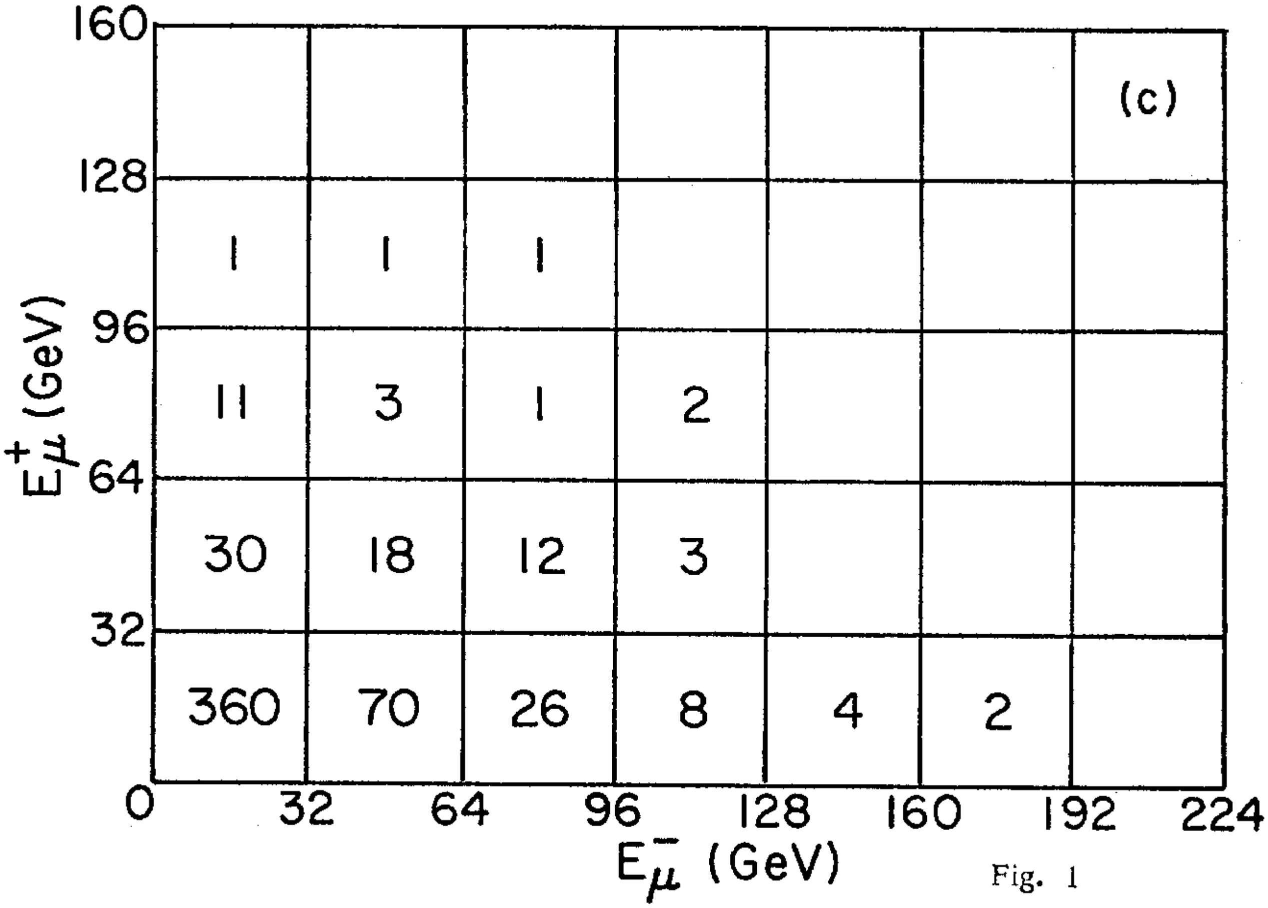
(c)
160
128
96
64
32
0
E_μ^+ (GeV)
1 1 1
11 3 1 2
30 18 12 3
360 70 26 8 4 2
32 64 96 128 160 192 224
E_μ^- (GeV)

Fig. 1

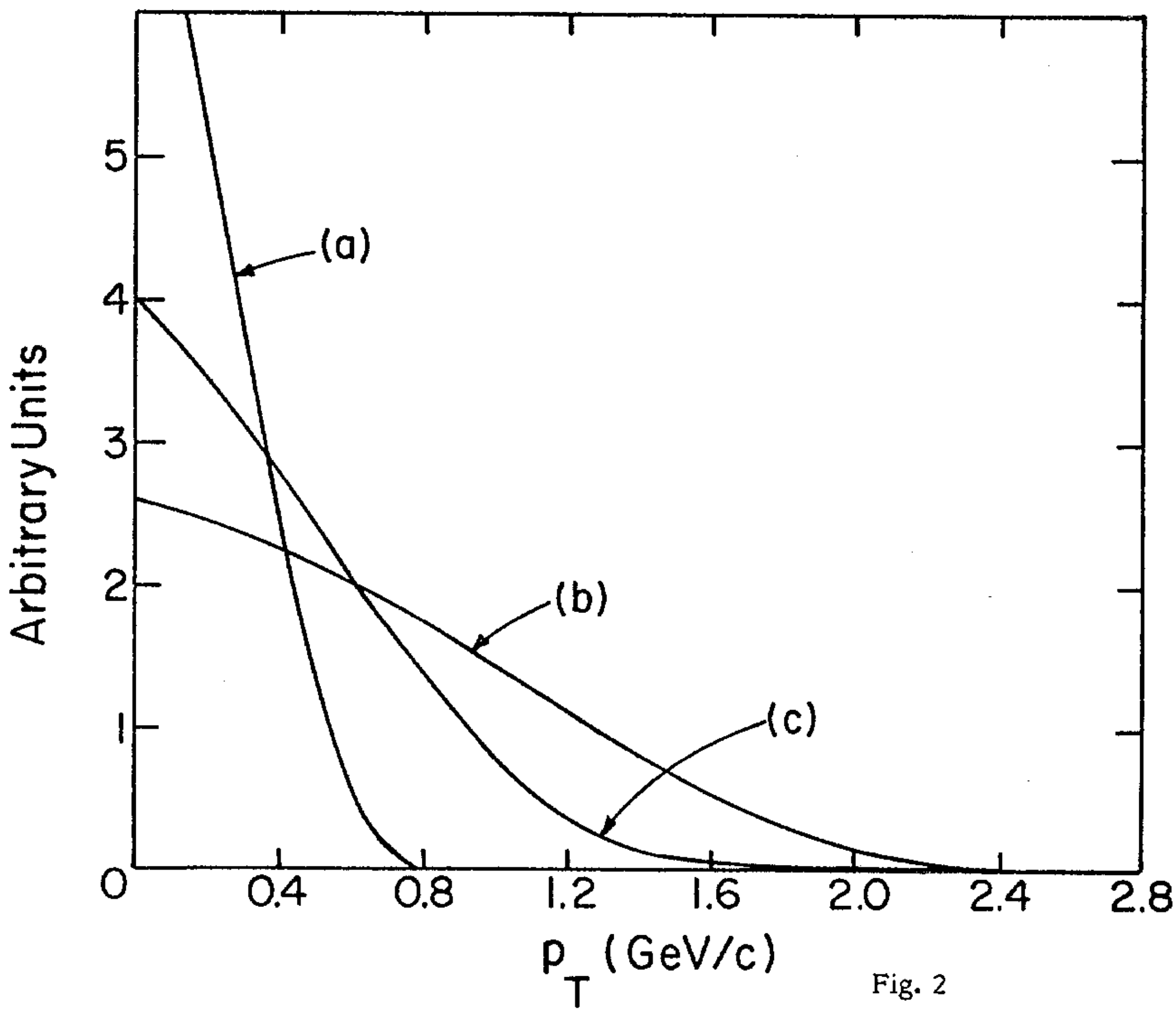
Arbitrary Units
0
1
2
3
4
5
(a)
(b)
(c)
0.4 0.8 1.2 1.6 2.0 2.4 2.8
p_T (GeV/c)

Fig. 2

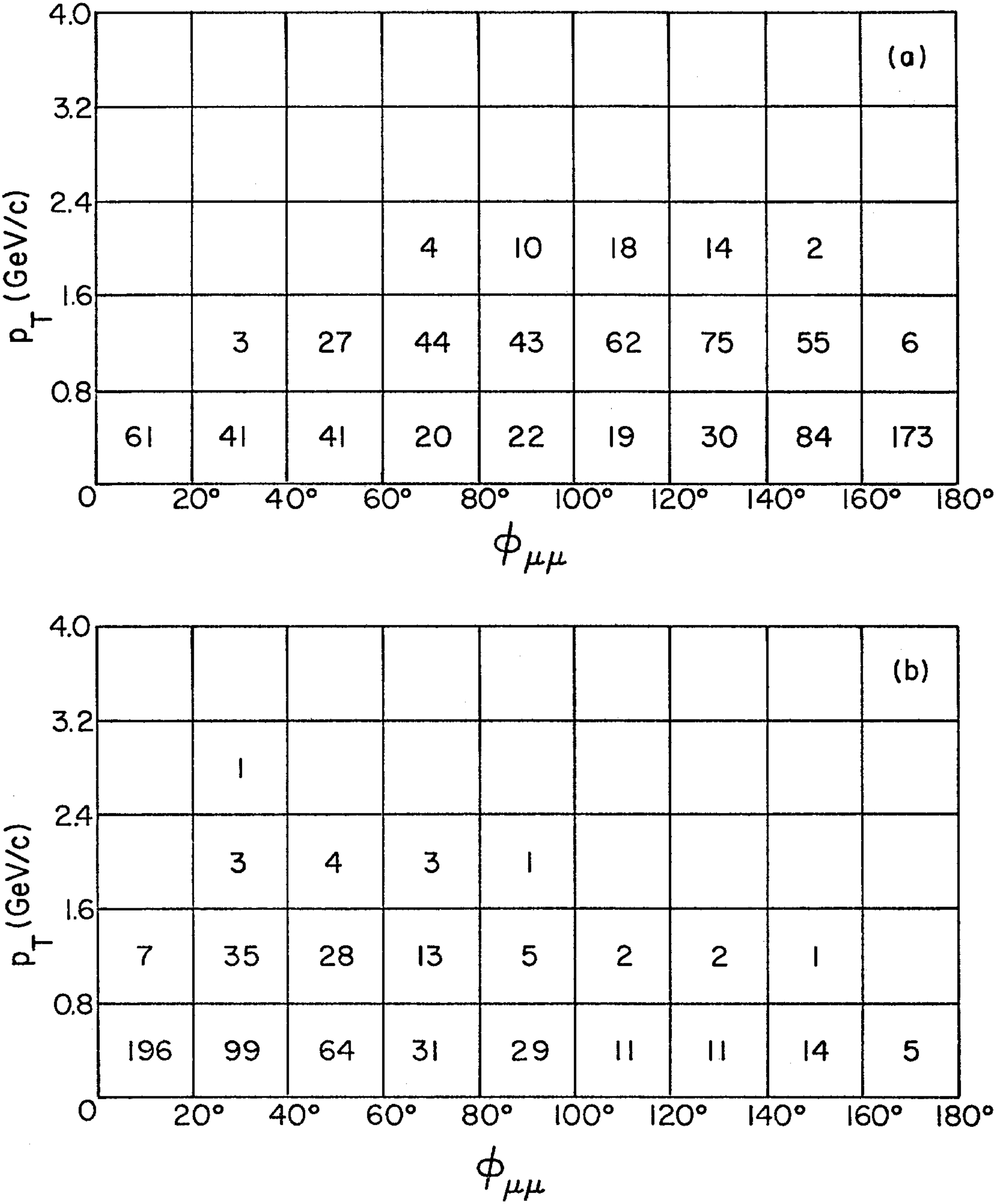
(a)
4.0
3.2
2.4
1.6
0.8
0
p_T (GeV/c)
4 10 18 14 2
3 27 44 43 62 75 55 6
61 41 41 20 22 19 30 84 173
20° 40° 60° 80° 100° 120° 140° 160° 180°
$\phi_{\mu\mu}$
(b)
4.0
3.2
2.4
1.6
0.8
0
p_T (GeV/c)
1
3 4 3 1
7 35 28 13 5 2 2 1
196 99 64 31 29 11 11 14 5
20° 40° 60° 80° 100° 120° 140° 160° 180°
$\phi_{\mu\mu}$

Fig. 3

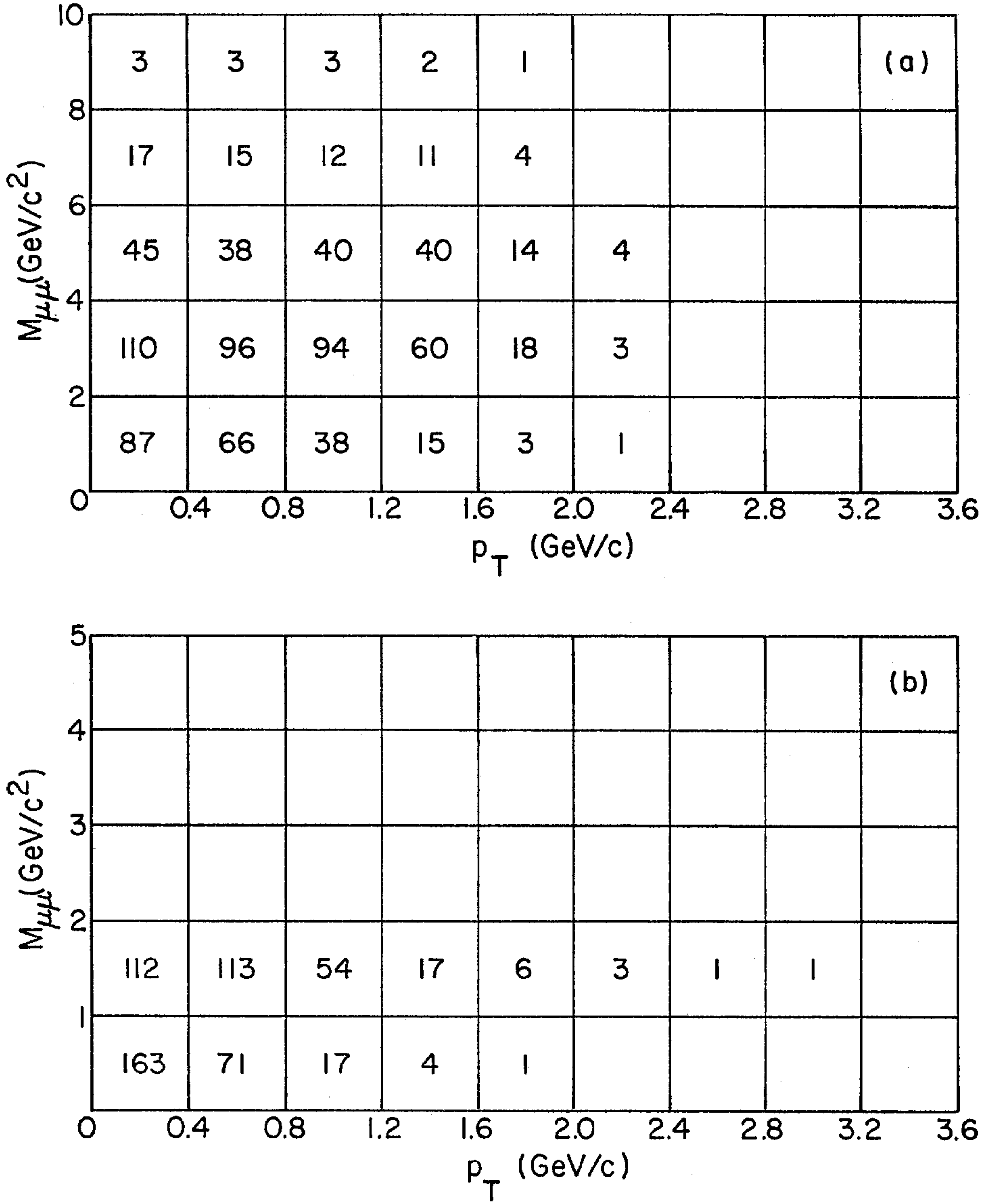
(a)
3 3 3 2 1
17 15 12 11 4
45 38 40 40 14 4
110 96 94 60 18 3
87 66 38 15 3 1
10
8
6
4
2
0
0.4 0.8 1.2 1.6 2.0 2.4 2.8 3.2 3.6
$M_{\mu\mu}$ (GeV/c^2)
p_T (GeV/c)
(b)
112 113 54 17 6 3 1 1
163 71 17 4 1
5
4
3
2
1
0 0.4 0.8 1.2 1.6 2.0 2.4 2.8 3.2 3.6
$M_{\mu\mu}$ (GeV/c^2)
p_T (GeV/c)

Fig. 4