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Mass Limit on a Positively Charged Heavy Muon*

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Abstract

We report a preliminary search for a positively charged lepton (Y^+) coupled directly to the μ^- and ν_μ (i.e., muon number = + 1). Using the production process $\nu_\mu + N \rightarrow Y^+ +$ anything, we have looked for the μ^+ from the decay $Y^+ \rightarrow \mu^+ + \nu_\mu + \nu_\mu$. The expected number of μ^+ events is given as a function of the heavy lepton mass, the branching fraction to muons, and the heavy lepton coupling. For typical gauge theory predictions, we obtain the 90% confidence limit $M_Y > 2$ GeV/c^2.

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One striking feature of weak interactions is the small number of members observed in the known lepton families. For example, the muon family presently contains only two observed members: ν_μ and μ^-. It is important to search for higher mass members, whose existence could have profound implications.

Considerable theoretical work[1,2] in the past few years has focused on unified gauge theories to predict controlled high energy behavior for the weak interactions and to unify the theoretical treatment of weak and electromagnetic interactions. Theories suggested thus far contain massive charged intermediate vector bosons ($M_W \sim 40$ GeV/c^2) together with neutral weak currents and/or heavy leptons. The suggested heavy leptons have the following properties: (1) They belong to existing lepton families (either electron or muon) and (2) They have different electric charge than existing charged leptons of the same lepton number.

The phenomenology of the proposed particles has been discussed at length by Bjorken and Llewellyn-Smith (BLS)[3] and by Llewellyn-Smith.[4] These authors mention several ways of searching for massive leptons. To date, we know that any heavy lepton must have a mass greater than that of the K-meson. Some calculations[3,5] have indicated that, were a positive heavy muon to exist with mass less than 1 GeV/c^2, it might have been observed in the CERN neutrino data.[6]

We emphasize here the production of heavy muons (Y^+), in a beam of high energy muon neutrinos. The ordinary mode of interaction for neutrinos of high energy is

$$\nu_\mu + N \rightarrow \mu^- + \text{hadrons}. \qquad (1)$$

The conjectured Y^+ would be produced by the process

$$\nu_\mu + N \rightarrow Y^+ + \text{hadrons}. \qquad (2)$$

Reaction (1) has been observed and measured at CERN[6] with neutrinos of energy $E_\nu \approx 1\text{-}10$ GeV. The results are consistent with neutrino scattering from spin $\frac{1}{2}$ fractionally-charged point-like constituents (quarks), with predominantly V-A coupling (mainly scattering off quarks rather than anti-quarks).[7] Preliminary NAL data is also qualitatively consistent with this picture at higher energies.[8][9]

In the quark model, the differential cross section for either (1) or (2) is given by

$$\frac{d^2\sigma_\pm}{dx\,dy} = \frac{g_\pm^2\, s}{\pi(sxy+M_W^2)^2}\left\{2xf(x)\left(1-\frac{m_\pm^2}{sx}\right) + 2x\bar{f}(x)(1-y)\left(1-y-\frac{m_\pm^2}{sx}\right)\right\} \qquad (3)$$

where $g_+(g_-)$ is the coupling of the Y^+ (μ^-) to the muon neutrino

s is the square of the center-of-mass energy

M_W is the mass of the charged intermediate vector boson (assumed large)

x,y are the deep-inelastic variables ($x = Q^2/2M\nu$, $y = \nu/E_\nu$)

$2xf(2x\bar{f})$ is the momentum distribution for quarks (anti-quarks) in the nucleon (related to the deep-inelastic structure functions)

$m_+(m_-)$ is the mass of the Y^+ (μ^-)

Figure 1 shows the ratio of total cross sections expected for reactions (2) and (1), obtained by integrating Eq. (3) over the available phase space, and assuming that $g_+^2 = g_-^2$. For this calculation, we have taken $xf(x) \propto F_2(x)^{ed}$, i.e., the scaling structure function found in inelastic electron-deuteron scattering[10], and $\bar{f}(x) = 0$. Inclusion of the small anti-quark component[7]

implied by the low energy CERN neutrino data changes Fig. 1 by a negligible amount. The calculation also assumes that $M_W^2 \gg s$.

The decay modes expected for the Y^+ are

$$Y^+ \rightarrow \nu_\mu + \mu^+ + \nu_\mu \tag{4}$$

$$Y^+ \rightarrow \nu_\mu + e^+ + \nu_e \tag{5}$$

$$Y^+ \rightarrow \nu_\mu + \text{hadrons} \tag{6}$$

The search described here is for μ^+ from the decay (4). If these are the only modes available, it has been estimated that [3]

$$B \equiv \Gamma(Y^+ \rightarrow \nu_\mu + \mu^+ + \nu_\mu)/\Gamma(Y^+ \rightarrow \text{anything}) \simeq 0.3$$

for $1 < M_Y < 6$ GeV/c^2. However, if there exists an uncharged heavy muon, Y^0, which is lighter than the Y^+, other decays of the type $Y^+ \rightarrow Y^0$ + anything might be expected. The exact contribution is somewhat model and mass-dependent, though phase space considerations alone should make such decay rates small in comparison to (4), (5) and (6).

In our experiment, a narrow band, sign-selected beam of positive pions and kaons, of mean energy 160 GeV, was allowed to decay to neutrinos ($\pi^+ \rightarrow \mu^+\nu_\mu$ or $K^+ \rightarrow \mu^+\nu_\mu$). The forward neutrinos entered our apparatus, giving two bands of neutrino energy: from K-decay, $\langle E_\nu \rangle \simeq 145$ GeV; from π-decay, $\langle E_\nu \rangle \simeq 50$ GeV. This run has been described previously [11] in a communication describing a search for the charged intermediate boson. The same data, consisting of 112 reconstructed neutrino interactions, are used in the present paper. For this search, the sign-selected nature of the beam is of prime importance. The only reaction that might be expected to produce a background μ^+ in our sample is

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + \text{hadrons} \tag{7}$$

from background π^- or K^- decays.

The run reported here consisted of 2.65×10^{16} protons on target. Of the 112 events inside the fiducial volume which could be reconstructed kinematically, 111 had a definite μ^- secondary. Subsequent analysis[8] showed that these events are consistent with production from reaction (1), assuming quark model structure functions.

There existed in this run a single μ^+ event with observed hadron energy $E_h \simeq 2$ GeV, muon energy $E' = 57$ GeV, and muon angle $\theta' \approx 34$ mrad. If this event corresponded to decay of a Y^+, its mass would be several GeV/c^2. However, we believe that this event comes from $\bar{\nu}_\mu$ contamination (7) for the following reasons:

(1) independent background runs demonstrated the existence of wide-band anti-neutrino background at roughly the one event level;

(2) this event has small hadron energy. This is more characteristic of $\bar{\nu}$ interactions than of heavy lepton production. Fig. 2 shows the fraction of μ^+ events expected, for both cases, in which the ratio (y) of observed hadron energy to observed total energy is less than y_u. The curves include the apparatus acceptance, and incorporates the cross section (3). The observed event had $y = 0.03$. About 1% of Y^+ decays might be expected to have $y \leq 0.03$, while about 20% of $\bar{\nu}$ interactions are expected with $y \leq 0.03$. This occurs principally because the secondary μ^+ in $\bar{\nu}_\mu$ interactions takes a large fraction of the energy,[7] while the μ^+ from the predominantly left-handed Y^+ has low laboratory energy. We conclude that this anomalous event is most likely from $\bar{\nu}_\mu$ contamination.

To calculate our sensitivity, we have used a Monte-Carlo calculation which assumes the cross section (3), and takes into account the polarization of the Y^+ and subsequent decay angular distribution via reaction (4). Figure 3 shows $N\left(\frac{g_-}{g_+}\right)^2 \frac{0.3}{B}$, where N is the number of μ^+ events expected in this run, as a function of heavy lepton mass, M_Y. For simple gauge theories, we have $g_+^2 = g_-^2$, and for specific assumptions for the decay probability[3], we have $B \simeq 0.3$. With these assumptions, the ordinate corresponds to the expected number of events in the experiment. The one-event level is in the region of $M_Y \sim 5$ GeV/c^2. The Poisson probability for observing 1 event when the mean is 3.56 is equal to 0.1. We can therefore quote a lower mass bound on a Y^+ as $M_Y > 2$ GeV/c^2, with 90% confidence. For differing assumptions regarding the lepton coupling or branching ratio, the limit can be adjusted.

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Figure Captions

1. Ratio of Y^+ production to μ^- production in a beam of muon neutrinos of energy E_ν. The quark model structure function relationships are assumed.

2. The calculated fraction, F, of events in our apparatus with $y < y_u$, where $y = E_h/E_{tot}$. The curves correspond to the reactions $\nu + N \rightarrow Y^+ + \text{anything}$, and $\bar{\nu} + N \rightarrow \mu^+ + \text{anything}$. Quark model

   $\hookrightarrow \mu^+ + \nu_\mu + \nu_\mu$

   structure functions are assumed. The single observed μ^+ event is indicated.

3. $N\left(\frac{g_-}{g_+}\right)^2 \frac{0.3}{B}$ as a function of heavy lepton mass, M_Y. N is the expected number of μ^+ events in the experiment, B is the branching ratio for $Y^+ \rightarrow \nu_\mu + \mu^+ + \nu_\mu$, and $g_+(g_-)$ is the weak coupling of the heavy lepton (muon) to the neutrino and the weak current.

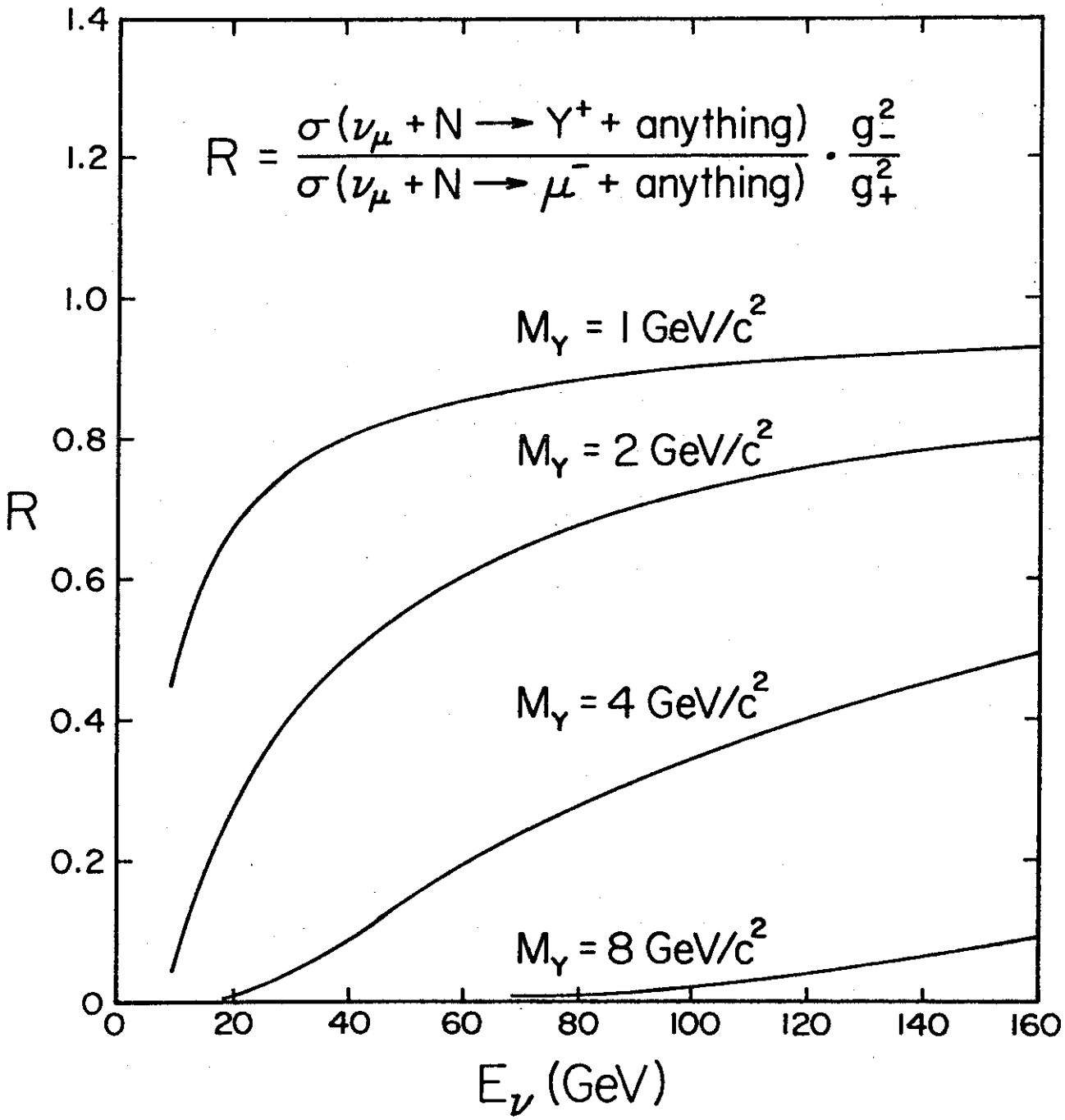
$R = \frac{\sigma(\nu_\mu + N \rightarrow Y^+ + \text{anything})}{\sigma(\nu_\mu + N \rightarrow \mu^- + \text{anything})} \cdot \frac{g_-^2}{g_+^2}$
$M_Y = 1\ \text{GeV}/c^2$
$M_Y = 2\ \text{GeV}/c^2$
$M_Y = 4\ \text{GeV}/c^2$
$M_Y = 8\ \text{GeV}/c^2$
R
E_ν (GeV)
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
20
40
60
80
100
120
140
160

Fig. 1

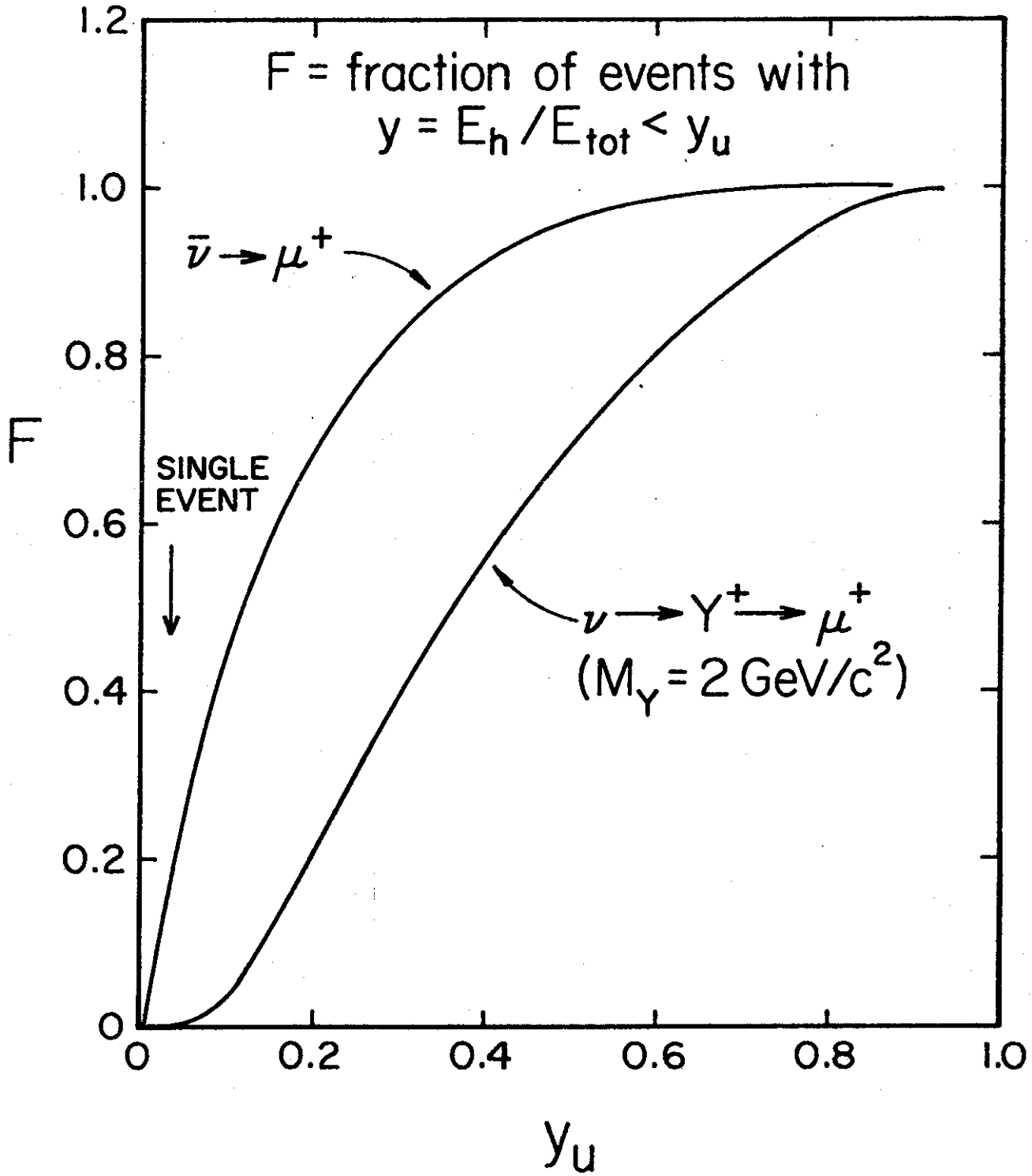
F = fraction of events with
y = E_h / E_tot < y_u
1.2
1.0
0.8
0.6
0.4
0.2
0
F
SINGLE EVENT
ν̄ → μ+
ν → Y+ → μ+
(M_Y = 2 GeV/c²)
0
0.2
0.4
0.6
0.8
1.0
y_u

Fig. 2

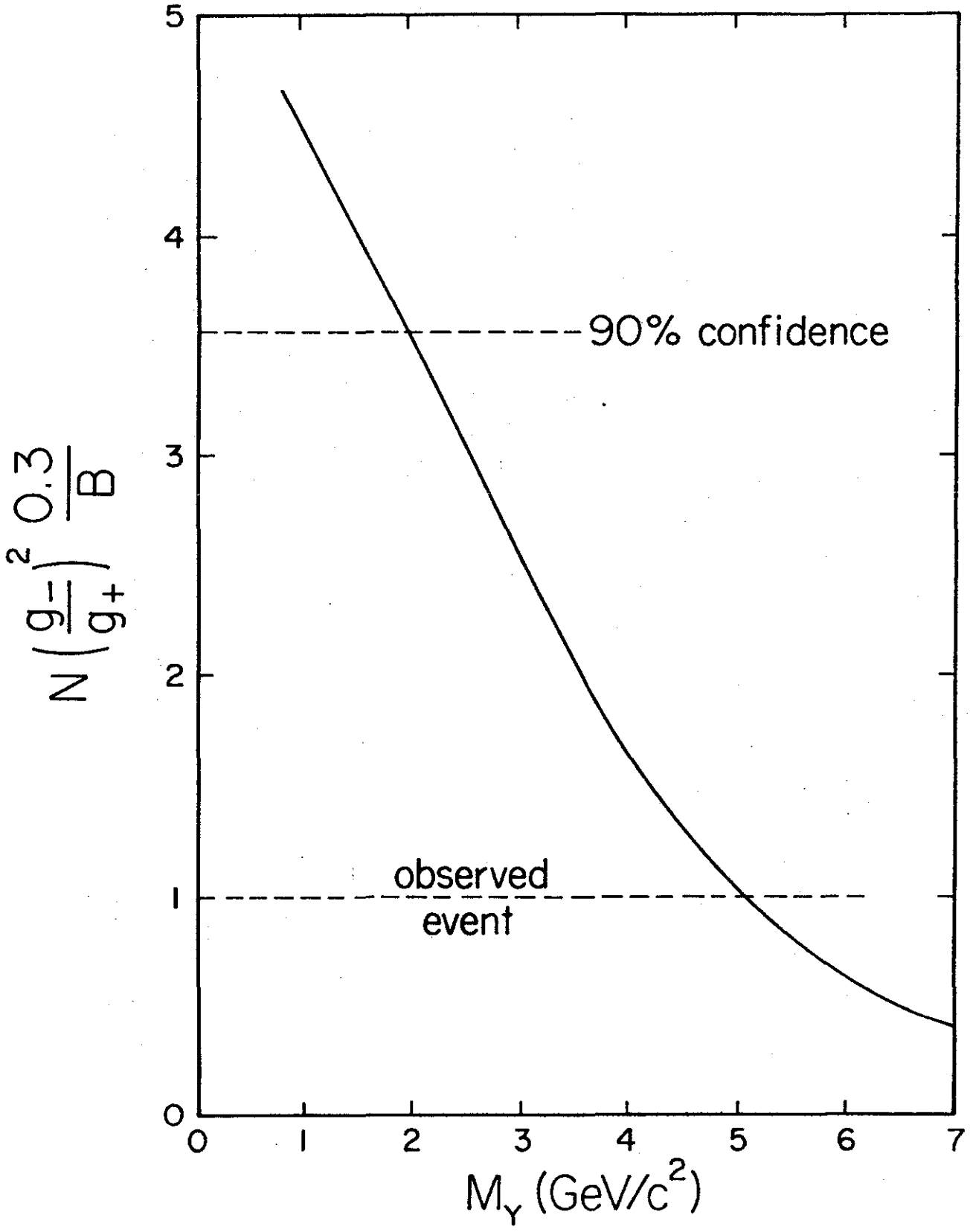
5
4
3
2
1
0
0
1
2
3
4
5
6
7
90% confidence
observed
event
$N\left(\frac{g_-}{g_+}\right)^2 \frac{0.3}{B}$
M_Y (GeV/c^2)

Fig. 3