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Analysis of 122 965 dimuon final states produced by 209-GeV muons in a magnetized iron calorimeter has set a lower limit on the mass of a neutral heavy muon ($\bar{M}^0$). If the $\bar{M}^0$ is coupled with Fermi strength to a right-handed charged current and decays to $\mu\mu\nu$ with a 10% branching ratio, its mass exceeds 9 GeV/c^2.

We report a limit on the muoproduction of a neutral and a doubly charged heavy muon ($\bar{M}^0$ and M^{++}) based on the analysis of 76 350 opposite-sign and 46 615 same-sign dimuon final states produced by 1.4×10^{11} positive and 2.9×10^{10} negative 209-GeV muons in the Berkeley-Fermilab-Princeton multimuon spectrometer at Fermilab.

The muon beam was incident on a solid steel dipole magnet composed of (91) 10-cm-thick steel plates interleaved with scintillation counters and wire chambers. The steel served as target, hadron calorimeter, muon identifier, and momentum analyzing spectrometer. The trigger and reconstruction algorithms have been described elsewhere[1,2]. The analyzed data are sensitive to $\bar{M}^0$ and M^{++} production in the mass range $1<m_M<14$ GeV/c^2.

Considerable speculation has been devoted to the possible existence of heavy neutral gauge leptons. Variations of the standard SU(2)×U(1) model[3] have been proposed which include[4] M^0's. Grand unification schemes frequently introduce M^0's, e.g. those[5] which embed $SU(2)_L\times U(1)_R$ in $SU(3)_L\times SU(3)_R$. In addition to the M^0, heavy doubly charged gauge muons (M^{++}) have been proposed in the context of an extended SU(2)×U(1) theory in doublets with the known singly charged leptons[4].

There exist few experimental limits on the masses of heavy muons. Studies of π and K decay[6] exclude the M^0 mass from the range $m_\mu<m_{M^0}<m_K$. A bubble chamber study of ν_μ-N interactions[7] sets a 90%-confidence lower limit of 1.8 GeV/c^2 on the mass of the heavy muon M^-. Although there are 90%-confidence lower limits on the M^+ mass of 2.4 GeV/c^2 from ν_e-N scattering[8] and 8.4 GeV/c^2 from ν_μ-Fe interactions[9], there is no further experimental constraint on the M^0 mass.

Possible evidence for M^0 production has arisen from three experiments. Two μ^-e^+ events produced by ν_μ-N interactions below 30 GeV in the SKAT bubble chamber[10] were attributed[11] to the production of an M^0 with $1.4<m_{M^0}<2.4$ GeV/c^2. However, no corroborating evidence for the M^0 has resulted from further study[12] of ν and $\bar{\nu}$ induced μe pairs. In a cosmic ray experiment[13] deep underground, five events were interpreted to be either the production of a lepton with mass 2-4 GeV/c^2 or the cascade[14] of a new charged heavy lepton to an M^0. However, two subsequent searches[15] found no such events. Originally the observation of neutrino-induced trimuon events at Fermilab[16] prompted their interpretation[17] as examples of M^0 production. Further experiments and analyses found this phenomenon to be compatible with conventional processes: heavy lepton production could account for no more than 10-20% of these events[18].

We have calculated the expected rates for $\bar{M}^0$ and M^{++} production in this experiment, assuming the incident muon to be coupled with Fermi strength to the M by means of a right-handed weak current. The right-handed coupling, present in most models containing a heavy gauge lepton, is compatible with our experimental conditions due to the $\gtrsim$80% left-handed polarization of the μ^+ beam[19]. In the limit of negligible muon mass, invariance to weak isospin rotation gives $\sigma(\mu^-(L.H.)N\to\nu_\mu X)=\sigma(\nu_\mu N\to\mu^- X)$, where L.H. refers to the left-handed muon helicity and N is an average of proton and neutron. Also, for negligible M^0 mass, $\sigma(\mu^-(L.H.)N\to M^0 X)=(g_L/g)^2\sigma(\mu^-(L.H.)N\to\nu_\mu X)$, where $g_L{}^2/g^2$ is the ratio of left-handed coupling strengths for M^0 and ν_μ. Finally, $\sigma(\mu^+(L.H.)N\to\bar{M}^0 X)=(g_R/g_L)^2\,\sigma(\mu^-(L.H.)N\to M^0 X)$, where $g_R{}^2/g_L{}^2$ is the ratio of abnormal-helicity to normal-helicity weak coupling strengths[20] for the M^0. For a right-handed current of Fermi strength this ratio is unity. Except for effects of finite lepton mass, these equations combine to give $\sigma(\mu^+(L.H.)N\to\bar{M}^0 X)=(g_R/g)^2\sigma(\nu_\mu N\to\mu^- X)$.

Using the simplest parton model with single W^+ exchange[21], invoking the

Callan-Gross relation[22], and considering only $\Delta S = \Delta C = 0$ processes and isoscalar targets,

$$\frac{d^2\sigma(\mu^+(L.H.)N\to\bar{M}^0X)}{d\nu dy} = \left(\frac{g_R}{g}\right)^2 \frac{G^2Em_NF_2(x)}{\pi y} \quad ,$$

where $\nu=xy=Q^2/s$, $(1-y)$ is the fraction of the laboratory muon energy E retained by the $\bar{M}^0$, and $F_2(x)=18\nu W_2^{\gamma N}(x)/5$. We parameterize $\nu W_2^{\gamma p}$ as in Ref. 23 and set[24] $\nu W_2^{\gamma N}=(1-0.4x)\nu W_2^{\gamma p}$. The differential cross section is independent of $\bar{M}^0$ mass, except for kinematic restriction of the allowed area of the Q^2-ν plane.

The differential decay rate for $\bar{M}^0\to\mu^+\mu^-\bar{\nu}_\mu$, where the $\bar{M}^0$ is coupled to the μ^+ by a (V+A) current, is

$$\frac{d^5\Gamma(\bar{M}^0\to\mu^+\mu^-\bar{\nu}_\mu)}{dx_-dx_\nu d\phi_\nu d\cos\theta_\nu d\phi_-} \propto x_\nu(1-x_\nu)(1-h\cos\theta_\nu) .$$

In the $\bar{M}^0$ rest frame $x_-(x_\nu)$ is $2p/m_{M^0}$ for the $\mu^-(\bar{\nu}_\mu)$, θ_ν and ϕ_ν define the $\bar{\nu}_\mu$ direction relative to the $\bar{M}^0$ direction, θ_- and ϕ_- define the μ^- direction relative to the $\bar{\nu}_\mu$ direction, and h is the $\bar{M}^0$ helicity. Since the $\bar{M}^0$ carries the left-handed polarization of the incident μ^+, the two muons are emitted preferentially forward and together carry an average of 80% of the $\bar{M}^0$ energy in the laboratory.

Monte Carlo events have been generated according to the above formulae at lepton masses of 1,2,3,6,9,12 and 14 GeV/c^2. Our simulation of the apparatus has been well tested in the analysis of J/ψ[1] and charmed meson[2] production. Simulated $\bar{M}^0$ and M^{++} events at each mass are binned in $\sqrt{Q^2}$ and in $p_\perp$, the daughter muon momentum transverse to $\vec{Q}$. For this analysis, Q^2 is defined by taking the highest-energy beam-sign final state muon to be a scattered beam muon. The $\bar{M}^0$ (M^{++}) Monte Carlo events are compared to data events containing exactly two opposite- (same-) sign reconstructed final state muons.

Kinematic cuts were chosen individually for each heavy lepton type and mass in order to exclude data while retaining Monte Carlo $\bar{M}^0$ events. These cuts require a minimum energy deposited in the calorimeter, a minimum outgoing muon energy, a minimum missing energy, and a particular range of dimuon invariant mass. The cuts suppress the principal backgrounds of charm production and π- and K-decay. An empirical contour then was drawn for each $\sqrt{Q^2}$-$p_\perp$ plot in order to contain all the data events on the low $p_\perp$, low $\sqrt{Q^2}$ side. The same contour was drawn on the corresponding plot for simulated $\bar{M}^0$ events. (If the same contour[25] and cuts, except for the dimuon mass cut, were used for all masses, the limits presented below would rise by a factor of 1.6 on the average). Figure 1 shows the plots and contour for data and Monte Carlo corresponding to 6 GeV/c^2 $\bar{M}^0$ production. The 3.5 Monte Carlo events on the high $p_\perp$, high $\sqrt{Q^2}$ side of the contour then provide the cross section limit at this mass.

Figure 2 displays the mass-dependent limits on the product of cross section and $\mu\mu\nu$ branching ratio (σB) for $\bar{M}^0$ and M^{++} production. Also indicated are the calculated σB for the production of $\bar{M}^0$'s and M^{++}'s, where the branching ratio is assumed to be 0.1 and 0.2 for $\bar{M}^0$ and M^{++}, respectively. To 90% confidence the data exclude the production of an $\bar{M}^0$ or M^{++} coupled with Fermi strength to a right-handed current in the mass range $1<m_M<9$ GeV/c^2. Without a special mechanism to suppress pair production, doubly-charged leptons in this mass range would have been detected at PETRA. No comparable limits on $\bar{M}^0$ production in this range are available from any other experiment.

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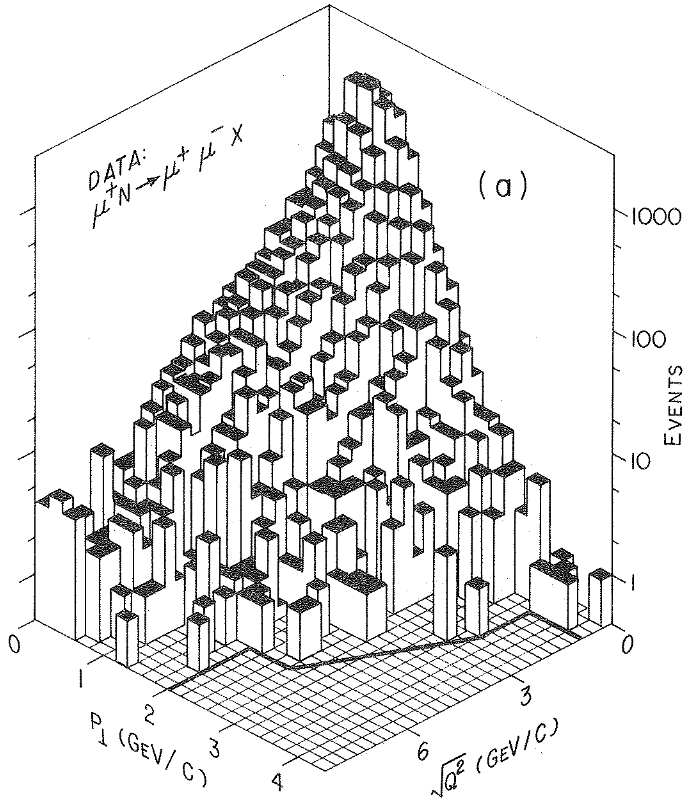
Figure Captions

FIG. 1. Two-dimensional event distributions vs. $\sqrt{Q^2}$ and $p_\perp$, defined in the text. The vertical scale is logarithmic; bin populations range from 0 to 450. Distribution (a) shows the data and an empirically chosen contour within which these events are contained. Distribution (b) is 77.4× the simulated population from production and decay of a 6 GeV/c^2 $\bar{M}^0$, with the assumptions described in the text. The 3.5 events in (b) lying outside the contour in (a) give the quoted σB limit at this mass.

FIG. 2. Experimental upper limits and calculated cross section-branching ratio products σB for heavy-muon ($\bar{M}^0$ and M^{++}) production by 209-GeV muons, plotted vs. heavy muon mass. The calculation assumes $B(M \to \mu\mu\nu) = 0.1$ ($\bar{M}^0$) or 0.2 (M^{++}), and right-handed coupling of μ^+ to M with Fermi strength ($g_R = g_L$).



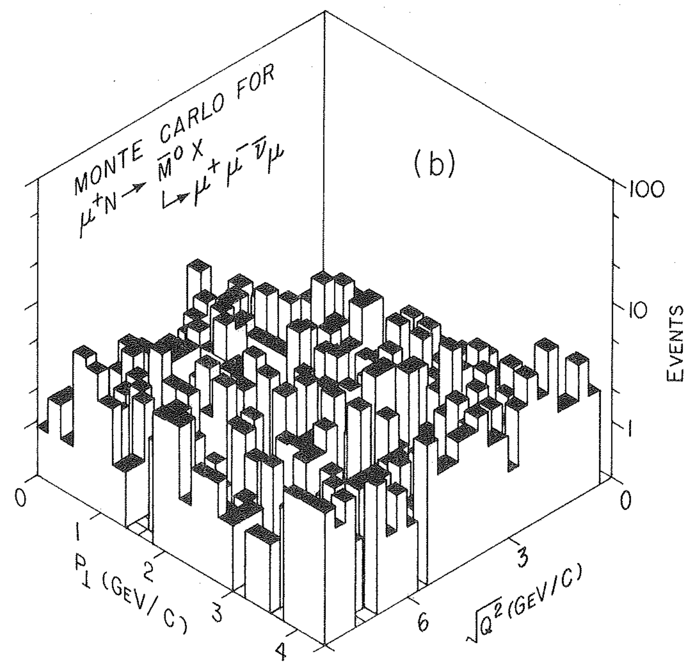


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FIG. 1

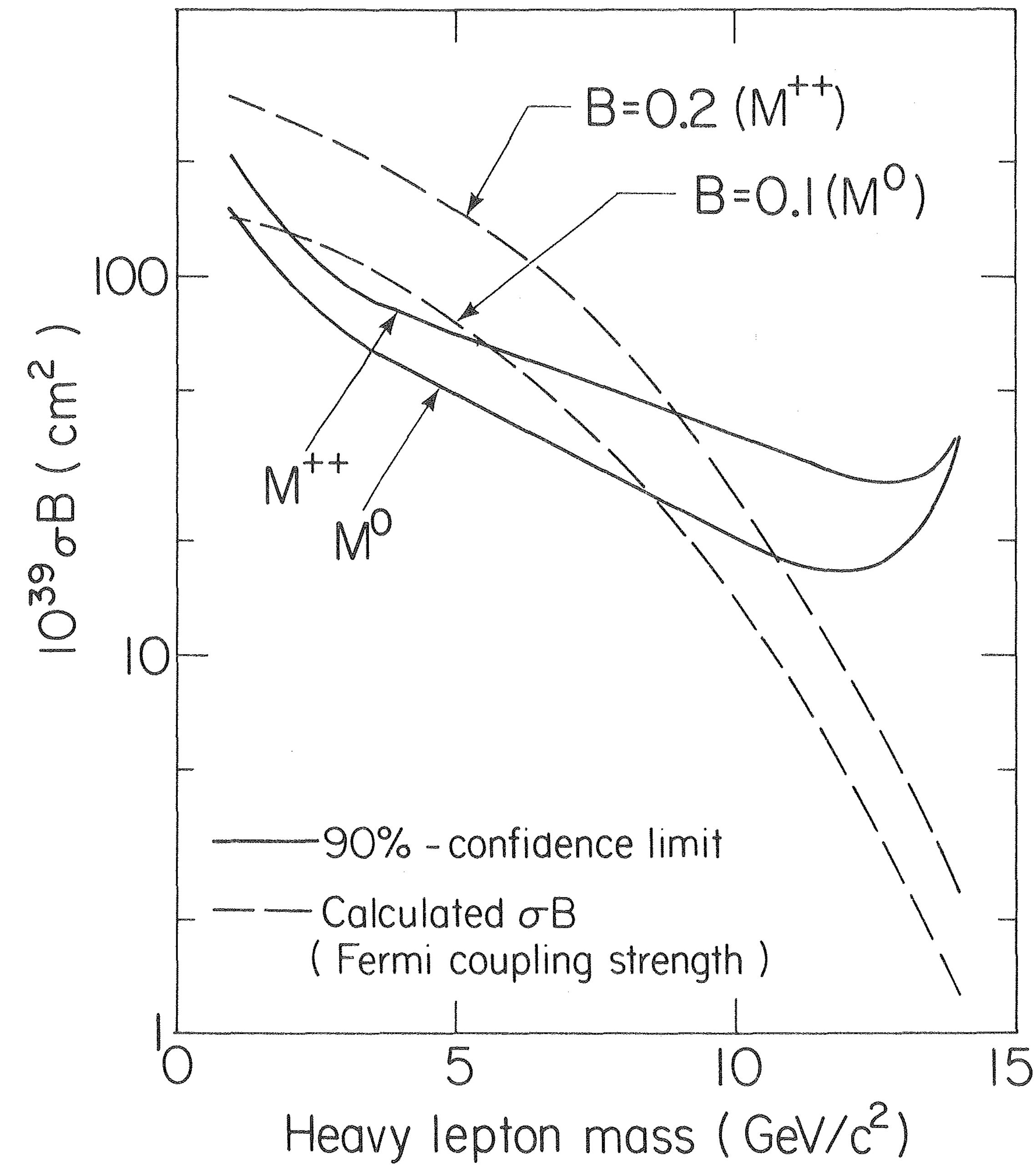

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FIG. 2