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Lower Limit on Neutral-Heavy-Muon Mass

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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.

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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 apparatus, 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)$\otimes$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 $[\mathrm{SU}(2)]_L\otimes[\mathrm{U}(1)]_R$ in $[\mathrm{SU}(3)]_L\otimes[\mathrm{SU}(3)]_R$. In addition to the M^0, heavy doubly-charged gauge muons (M^{++}) have been proposed in the context of an extended SU(2) $\otimes$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-level 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 $\mu^- e^+$ 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 because of the $\gtrsim 80\%$ left-handed polarization of the μ^+ beam.[19] In the limit of negligible muon mass, invariance to weak isospin rotation gives $\sigma[\mu^-(\mathrm{LH})N \to \nu_\mu \chi] = \sigma(\nu_\mu N \to \mu^- \chi)$, where LH refers to the left-handed muon helicity and N is an average of proton and neutron. Also, for negligible M^0 mass, $\sigma[\mu^-(\mathrm{LH})N \to M^0\chi] = (g_L/g)^2 \times \sigma[\mu^-(\mathrm{LH})N \to \nu_\mu \chi]$, where g_L^2/g^2 is the ratio of left-handed coupling strengths for M^0 and ν_μ. Finally, $\sigma[\mu^+(\mathrm{LH})N \to \bar{M}^0\chi] = (g_R/g_L)^2 \sigma[\mu^-(\mathrm{LH})N \to M^0\chi]$, 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 $\sigma[\mu^+(\mathrm{LH})N \to \bar{M}^0\chi] = (g_R/g)^2 \times \sigma(\nu_\mu N \to \mu^- \chi)$.

By 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,

$$\frac{d^2\sigma[\mu^+(\mathrm{LH})N \to \bar{M}^0\chi]}{d\nu\, dy} = \left(\frac{g_R}{g}\right)^2 \frac{G^2 E m_N F_2(x)}{\pi y},$$

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 parametrize $\nu W_2^{\gamma p}$ 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

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

In the $\bar{M}^0$ rest frame x_- (x_ν) 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 formulas 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. Primarily, these cuts demand a particular range of dimuon invariant mass.[25] In addition, for $m_{M^0} > 3$, > 2, or < 3 GeV/c^2, respectively, the cuts require a 9 GeV minimum outgoing muon energy, a -5 GeV minimum missing energy, or a 60 GeV minimum ν. The cuts suppress the prinicpal 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[26] 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.

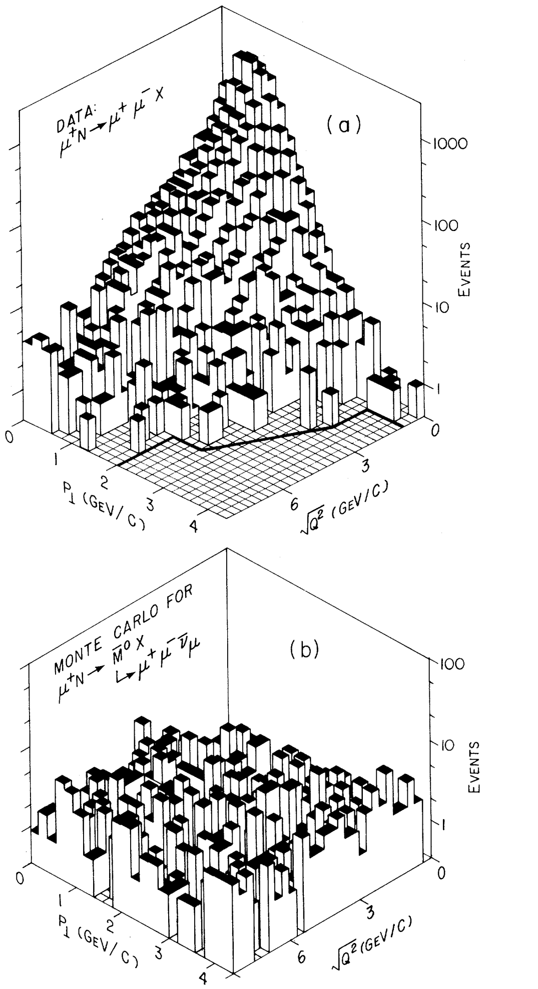

FIG. 1. Two-dimensional event distributions vs $\sqrt{Q^2}$ and $p_\perp$, defined in the text. The vertical scale is logarithmic; bin populations range from 0 to 450. Distribution (a) shows the data and an empirically chosen contour within which these events are contained. Distribution (b) is 77.4 times 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.

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. At 90% confidence level, the data exclude

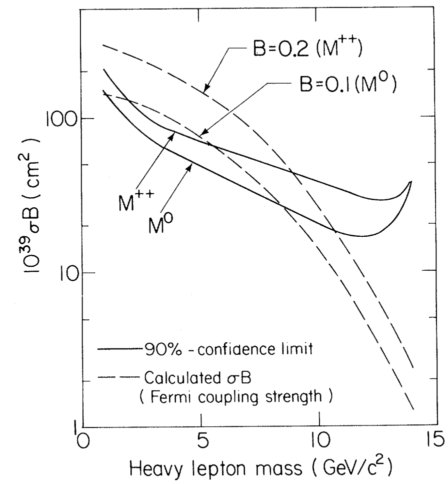

FIG. 2. Experimental upper limits and calculated cross-section–branching-ratio products σB for heavy-muon ($\bar{M}^0$ and M^{++}) production by 209-GeV muons, plotted vs heavy muon mass. The calculation assumes $B(M\to\mu\mu\nu)=0.1$ ($\bar{M}^0$) or 0.2 (M^{++}), and right-handed coupling of μ^+ to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

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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[24]This approximation is an empirical fit to data in S. Stein *et al.*, Phys. Rev. D 12, 1884 (1975).

[25]The mass range used is approximately $0.34\, m_{M^0} \leq m \leq m_{M^0}$.

[26]The contour outlines the region $\sqrt{Q^2} > 3.0$ and $p_\perp > 3.44 - 0.11\sqrt{Q^2}$.

Glueball Spectrum in Extended Quantum Chromodynamics

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Extended quantum chromodynamics in which the magnetic structure of the color gauge symmetry plays the important role in the dynamics is proposed as a phenomenological theory of the strong interaction. In the one-loop approximation the masses of the scalar and the axial-vector magnetic glueballs are estimated to be around 2.2 and 1.5 GeV, and the leading linear trajectory of the 2^{++} electric glueball is estimated to be $\alpha_x(s) \simeq 0.48s\,(\mathrm{GeV}^{-2}) + 1.01$. The trajectory is proposed as the Pomeron.

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One of the most challenging problems in contemporary physics is to clarify the physical meaning of quantum chromodynamics (QCD), in particular to obtain the physical spectrum of the theory. To resolve this problem we have recently constructed *the extended gauge theory*, or *the gauge theory in the large*,[1] in which the magnetic structure of the underlying gauge symmetry plays the important role in the dynamics. Based on the group SU(2), the extended theory has been shown to exhibit a manifest confinement of the color. More importantly the theory could tell us how to construct the physical states, in particular the glueball states, and to calculate its mass spec-