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Effects of exotic composite bosons in e^+e^- scattering at 50–100 GeV

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We show that some of the neutral exotics in the composite model decouple from neutrinos at low energies, and can be as light as the mass scale of the weak interactions, offering the possibility of detecting sizable effects in e^+e^- scattering at 50–100 GeV.

Regularities in the quark-lepton spectra seem to suggest a further fundamental layer of matter, the subquark (or preon).[1-3] For example, the proliferation of color triplets and weak isodoublets may indicate the subquarks *c* and *w*, the common carriers of the color and the weak isospin, respectively. In this picture, weak bosons, Higgs-boson scalars, and even the photon and gluon could also be composite.[2] The composite models predict various new phenomena at energies as high as the compositeness scale. New exotic and excited states should appear,[4] the scattering cross sections should deviate from their standard-model values due to their size effects,[5] and subquarks should develop jets consisting of quarks, leptons, and intermediate bosons.[6] From the argument of unnaturalness in the mass renormalization of the Higgs-boson sector in the standard model, the scale of new physics cannot be much beyond the TeV region.[7] If compositeness is responsible for avoiding unnaturalness, the above-mentioned phenomena would be observed in this region. In particular, we expect that the ground states of the neutral exotics can be observed at comparatively low energies. In this paper we examine the possibilities of observing their effects in the energy regions of the experiments with the e^+e^- colliders such as TRISTAN at KEK, the SLAC Linear Collider (SLC), and LEP at CERN.

The neutral exotics should exhibit their effects also in $p\bar{p}$ scattering, neutrino scattering, the anomalous magnetic moments of leptons, and the *Z*-boson mass deviation via mixing. Among them, neutrino scattering places the most severe restriction on their masses—larger than a few hundred GeV. Accordingly, they cannot affect e^+e^- scattering at 50–100 GeV so much, as long as they couple to neutrinos. The same restriction arises for the extra *Z* boson(s) in the grand unified and superstring-inspired models.[8] However, some of the neutral exotics in the composite models may decouple from neutrinos at low energies and are free from the restriction. We consider, as examples, (i) the "color-singlet gluon," the vector boson made of c and $\bar{c}$, where c is the subquark carrying the three colors and (ii) the heavy (excited) photon, which couples to matters with the strength proportional to their electric charges. For the purpose of comparison we also examine the effects of (iii) the "leptonic gluon,"[9] the vector boson made of c_l and $\bar{c}_l$, where c_l is the subquark carrying leptonic color, although this particle does couple to neutrinos.

Let us denote the exotic vector boson by V_μ. It is mixed with the photon $\tilde{A}_\mu$ (tilded because it is yet to be diagonalized to form the physical photon) and the neutral component of W_μ^3 of the weak boson through

$$\mathcal{L}_{\text{mix}} = -\tfrac{1}{2}\lambda \tilde{A}_{\mu\nu} W^{3\mu\nu} - \tfrac{1}{2}\lambda' \tilde{A}_{\mu\nu} V^{\mu\nu} - \tfrac{1}{2}\lambda'' W^3_{\mu\nu} V^{\mu\nu} + \Delta M^2 W_\mu V^\mu , \tag{1}$$

where $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ for the vector field B_μ in general; λ, λ', and λ'' are the current mixing parameters and ΔM is the mass mixing parameter. These bosons couple to matters through

$$\mathcal{L}_{\text{int}} = e J_\mu^{\text{em}} \tilde{A}^\mu + g J_\mu^3 W^{3\mu} + g_V J_\mu^V V^\mu , \tag{2}$$

where e is the electromagnetic coupling constant, g is the weak coupling constant, g_V is the coupling constant of V_μ, J_μ^{em} is the electromagnetic current, J_μ^3 is the neutral component of the weak-isospin current, and J_μ^V is the current of V_μ. As Hung and Sakurai pointed out, if and only if

$$\lambda = e/g , \tag{3}$$

then the known sector of the photon and weak bosons exactly coincides with that in the standard model,[10] and the model is phenomenologically acceptable.

The mixing parameters, the coupling constants, and the form of J_μ^V should be determined by the dynamics of the subquarks. People considered two complementary types of dynamics: that of the Nambu–Jona-Lasinio–Bjorken type[11,12] and that with fundamental gauge interactions.[13,14] The former is perturbatively solvable for composite states, though it requires an explicit momentum cutoff, and is not renormalizable. On the other hand, the latter is renormalizable and confining under appropriate conditions, while it is in general difficult to get explicit solutions for composite states. The latter, however, also includes cases where we can explicitly determine the composite spectrum[14] by virtue of complementarity between the Higgs phase and the confining phase.[15] To see the consequences of these dynamical models, we actually examined the following typical ones: (a) a model of the Nambu–Jona-Lasinio type and (b) an $SU(2)_L \times U(1) \times U(1)'$ gauge model, which are the straightforward extensions of the models in Refs. 16 and 17, respectively. The procedures illustrated in Refs. 16 and 17 lead to the following results. The relation (3) is safely satisfied, and

$$\lambda' = eQ_{c_l}/g_V, \quad \lambda''=0, \quad J^V_\mu = J^l_\mu \quad \text{for } V_\mu = \text{leptonic gluon}, \tag{4a}$$

$$\lambda' = eQ_c/g_V, \quad \lambda''=0, \quad J^V_\mu = J^q_\mu \quad \text{for } V_\mu = \text{color-singlet gluon}, \tag{4b}$$

$$\lambda' = e/g_V, \quad \lambda''=g_V/g, \quad J^V_\mu = J^{\text{em}}_\mu \quad \text{for } V_\mu = \text{heavy photon}, \tag{4c}$$

and $\Delta M^2 = 0$ for each case, where $Q_{c_l} = -\frac{1}{2}$ and $Q_c = \frac{1}{6}$ are the electric charge of the subquark c and c_l, respectively, and J^l_μ, J^q_μ, and J^{em}_μ are, respectively, the lepton number current, the quark number current, and the electromagnetic current of quarks and leptons. The heavy photon is equivalent to the boson V'_μ that couples to the weak hypercharge current J^Y_μ, whose interactions are described by

$$\mathcal{L}'_{\text{int}} = eJ^{\text{em}}_\mu \tilde{A}^\mu + gJ^3_\mu W'^{3\mu} + g'_V J^Y_\mu V'^\mu, \tag{2'}$$

and $\mathcal{L}_{\text{mix}}$ in (1) with

$$\begin{gathered} \lambda = e/g, \quad \lambda' = e/g'_V, \\ \lambda''=0, \\ \Delta M^2 = g'_V M_W^2/g, \end{gathered} \tag{4'}$$

where M_W is the mass of the W boson. The equivalence is established by the transformation

$$gW'^3_\mu = gW^3_\mu - g_V V_\mu, \quad g'_V V'_\mu = g_V V_\mu, \tag{5}$$

with $(g'_V)^{-2} = (g_V)^{-2} + g^{-2}$. Further details of these models will appear in a separate paper.[18] It is remarkable that the originally different dynamical models (a) and (b) lead to the same results (4a)–(4c). The fact that λ' has the form $e/g_V \times$(subquark charge) can be taken as a general consequence of the dynamics which respects relation (3). Thus, we expect that relations (4a)–(4c) hold in a fairly wide class of dynamical composite models. In the following we investigate the phenomenological consequences of these relations.

The current mixings in (4a)–(4c) are diagonalized by the following transformation that yields the physical photon A_μ, Z boson Z_μ, and extra vector boson X_μ:

$$\begin{bmatrix} A_\mu \\ Z_\mu \\ X_\mu \end{bmatrix} = \begin{bmatrix} 1 & \lambda & \lambda' \\ 0 & M_W\cos\phi/M_Z & -M_V\sin\phi/M_Z \\ 0 & M_W\sin\phi/M_X & M_V\cos\phi/M_X \end{bmatrix} \begin{bmatrix} \tilde{A}_\mu \\ W^3_\mu \\ V_\mu \end{bmatrix}, \tag{6}$$

where M_V is the mass of V_μ before the diagonalization, M_Z and M_X are the diagonalized masses of Z_μ and X_μ, respectively, and ϕ is the mixing angle defined by

$$\sin 2\phi = \frac{2M_X M_Z(\lambda\lambda' - \lambda'')}{(M_X^2 - M_Z^2)\sqrt{\Delta}} \tag{7}$$

with

$$\Delta = 1 - \lambda^2 - \lambda'^2 - \lambda''^2 + 2\lambda\lambda'\lambda''. \tag{8}$$

The masses M_W, M_V, M_Z, and M_X are related to each other by

$$M_W^2 M_V^2 = M_Z^2 M_X^2 \Delta, \tag{9}$$

$$(1-\lambda'^2)M_W^2 + (1-\lambda^2)M_V^2 = (M_Z^2 + M_X^2)\Delta. \tag{10}$$

Eliminating M_V we obtain the following relation among the observable masses:

$$[1-(1-\lambda^2)M_Z^2/M_W^2][1-(1-\lambda^2)M_X^2/M_W^2] = -(\lambda''-\lambda\lambda')^2/\Delta. \tag{11}$$

The interaction Lagrangian becomes

$$\begin{aligned} \mathcal{L}_{\text{int}} = eJ^{\text{em}}_\mu A^\mu &+ [(gJ^3_\mu - e\lambda J^{\text{em}}_\mu)\cos\phi/M_W - (g_V J^V_\mu - e\lambda' J^{\text{em}}_\mu)\sin\phi/M_V]M_Z Z^\mu \\ &+ [(gJ^3_\mu - e\lambda J^{\text{em}}_\mu)\sin\phi/M_W + (g_V J^V_\mu - e\lambda' J^{\text{em}}_\mu)\cos\phi/M_V]M_X X^\mu \end{aligned} \tag{12}$$

with λ's and J^V_μ given by (4a)–(4c).

The mixing parameters λ's are written in terms of the coupling constants, e, g, and g_V as in (4a)–(4c). Among them, e is precisely determined by experiments. We use the value such that $\alpha = e^2/4\pi = (1/137.036)(1-\Delta r)$, where $\Delta r = 0.058$ is the radiative correction with the top-quark mass $m_t = 100$ GeV and the Higgs-boson mass $M_H = 100$ GeV (Ref. 19). The coupling constant g is related to M_W by $g = (4\sqrt{2}G_F)^{1/2}M_W$, where the Fermi coupling constant G_F is precisely determined by β decay experiments. Thus, for a given set of $M_{W,Z,X}$, we can fix g_V by (11) and can calculate any physical quantities in terms of them. We show, by the solid lines in Fig. 1, the bounds[20] on M_X and g_V (or g'_V) from the constraint (11) with the averaged experimental values[21–23]

$$\begin{gathered} M_W = (80.0 \pm 0.56)\,\text{GeV}, \\ M_Z = (91.09 \pm 0.06)\,\text{GeV}. \end{gathered} \tag{13}$$

The solid lines in Fig. 2 show the bounds from the same conditions on $R(60\text{ GeV})$, $R(M_Z)$, and Γ_Z, where $R(E)=\sigma(e\bar{e}\rightarrow\text{hadrons})/\sigma(e\bar{e}\rightarrow\mu\bar{\mu})_{\text{QED}}$ at the c.m. energy E and Γ_Z is the decay width of the Z. Then we examine the following physical quantities, and compare them with the presently known experimental results (Figs. 1 and 2).

(i) *The Weinberg angle θ_W from neutrino scattering.* The angle θ_W determined by assuming the standard model is related to the quantities of the present model as

$$\sin^2\theta_W=\begin{cases}\dfrac{e^2}{g^2}\left[1+2Q_{c_l}\dfrac{M_W^2}{M_V^2}\right] & (\text{leptonic gluon},\nu p,\bar{\nu}p)\ ,\\[2ex] \dfrac{e^2}{g^2}\left[1+2\left[Q_{c_l}+\dfrac{g_V^2}{e^2}\right]\dfrac{M_W^2}{M_V^2}\right] & (\text{leptonic gluon},\nu e,\bar{\nu}e)\ ,\\[2ex] \dfrac{e^2}{g^2} & (\text{singlet gluon, heavy photon})\ .\end{cases} \tag{14}$$

Note that the singlet gluon and the heavy photon decouple from neutrinos at low energies, and suffer from no restriction from them. As the experimental value we use, following Costa *et al.*,[24] $\sin^2\theta_W=0.2283\pm0.0048$ (0.2271 ± 0.0143) from νp and $\bar{\nu}p$ (νe and $\bar{\nu}e$) scatterings.

(ii) *The compositeness scale Λ_c (Ref. 25) from Bhabha scattering.* The scale Λ_c is written in the present model as

$$\Lambda_c^2=2\pi M_V^2/(g_V N_e-eQ_e\lambda')^2\ , \tag{15}$$

where Q_ψ ($\psi=e,q$, etc.) is the electric charge of the fermion ψ, and N_ψ is the lepton number of ψ for V_μ = leptonic gluon, the quark number of ψ for V_μ = singlet gluon, and the electric charge of ψ for V_μ = heavy photon. The experimental bound is[26] $\Lambda_c>7.1$ TeV for current × current interactions with the vector coupling.

(iii) *The compositeness scale Λ_c from $p\bar{p}\rightarrow J$ + anything (J denotes a jet).* The scale Λ_c is written as

$$\Lambda_c^2=2\pi M_V^2\sum_q Q_q^2\Big/\sum_q Q_q^2(g_V N_q-eQ_q\lambda')^2\ , \tag{16}$$

where the summation is carried over the valence quarks u_v and d_v, and simple proportionality of their distribution functions is assumed. The experimental bound is[27] $\Lambda_c>700$ GeV, which is derived by assuming current × current interactions with the left-handed coupling. This is the only case analyzed by the authors of Ref. 27, and we use this value, though the coupling in the present model is vectorlike. It would be rather safe, because a crude estimate indicates that the value of Λ_c is larger for the vector coupling.

(iv) *$\sigma(p\bar{p}\rightarrow X+\text{anything})B(X\rightarrow JJ)$.* The experimental bound is given in Fig. 3 of Ref. 28 for $160<M_X<400$ GeV. In evaluating $\sigma(p\bar{p}\rightarrow X+\text{anything})$ in our model we use the parton distribution functions of the set I in Ref. 29.

(v) *$\sigma(p\bar{p}\rightarrow X+\text{anything})B(X\rightarrow e\bar{e})$.* The experimental bound is 1 pb (Ref. 30). In evaluating $\sigma(p\bar{p}\rightarrow X+\text{anything})$ in our model we again use the parton distribution functions of the set I in Ref. 29.

(vi) We have also examined the constraints from the

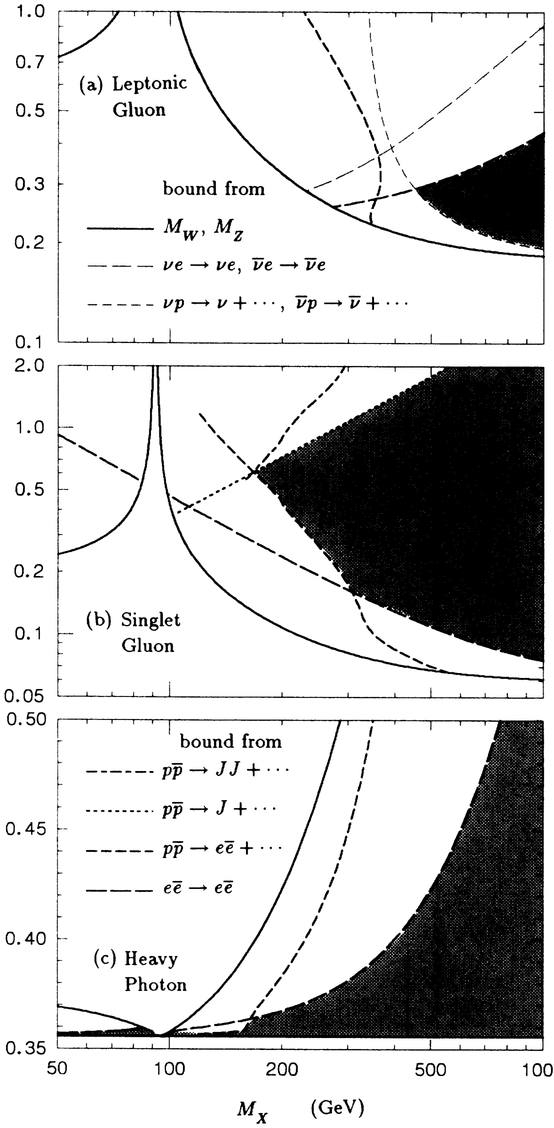

FIG. 1. The experimental bounds on g_V (or g_V') vs M_X for (a) leptonic gluon, (b) color-singlet gluon, and (c) heavy photon. The allowed regions are indicated by the shaded area. Each curve corresponds to the bound indicated in (a) and (c).

anomalous magnetic moments of the electron and muon, deep-inelastic lepton nucleon scattering, and parity violations in atoms. They are less restrictive than the above bounds because of their larger experimental errors.

The experimental bounds in (i)–(v), when combined with the ranges of the weak-boson masses in (13), give the bounds on M_X and g_V (or g'_V) shown in Fig. 1, and those on R(60 GeV), $R(M_Z)$, and Γ_Z shown in Fig. 2. The shaded regions are finally left allowed.

Since the mixing parameter λ' is proportional to $1/g_V$, a value of g_V too small causes mixing that is too large and is forbidden. When we have an experimental bound on a quantity concerning $X\psi\bar{\psi}$ vertex ($\psi=q,\nu,e$), g_V is bounded from above if V (X before mixing) directly couples to the $\psi\bar{\psi}$ channel, while g_V is bounded from below if X couples to the $\psi\bar{\psi}$ channel through mixing. Since neutrinos have a vanishing quark number and a vanishing electric charge, the singlet gluon and the heavy photon decouple from neutrinos at low energies, but the leptonic gluon couples to them through the lepton number. Consequently, νp, $\bar{\nu} p$, νe, and $\bar{\nu} e$ scattering experiments place restrictions on the mass of the leptonic gluon only: $M_X > 390$ GeV ($M_X > 450$ GeV when combined with the bound from $e^+e^- \to e^+e^-$) [Fig. 1(c)]. The leptonic gluon can hardly affect R(60 GeV), $R(M_Z)$, and Γ_Z. The singlet gluon is allowed in the region inside the bound from Λ_c in $p\bar{p} \to J + \cdots$, that from Λ_c in $e^+e^- \to e^+e^-$, and that from $p\bar{p} \to e^+e^- + \cdots$, which leaves the possibility of a mass as small as $M_X > 170$ GeV. For the heavy photon, the allowed region lies inside the

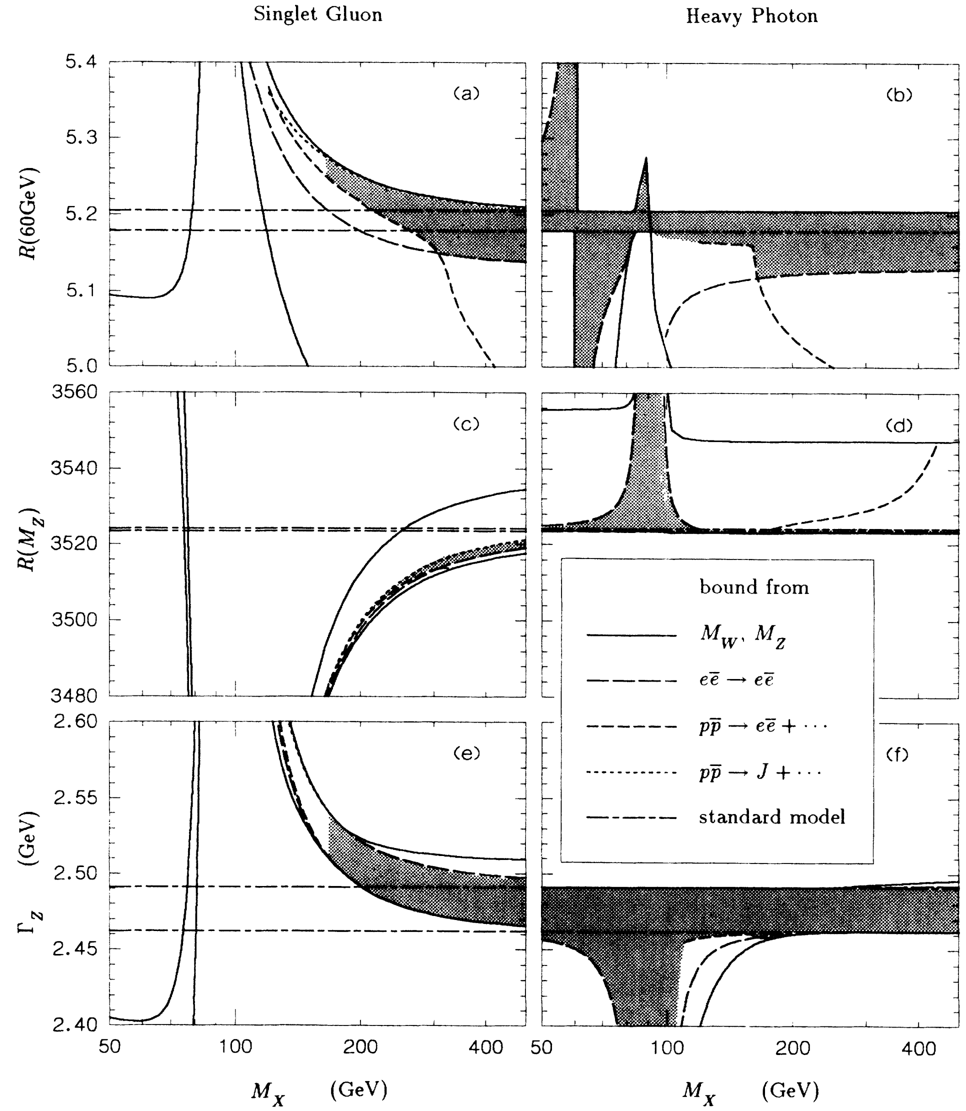

FIG. 2. The experimental bounds on R(60 GeV) [(a) and (b)], $R(M_Z)$ [(c) and (d)], and Γ_Z [(e) and (f)] vs M_X for the singlet gluon [(a), (c), and (e)] and for the heavy photon [(b), (d) and (f)]. The allowed regions are indicated by the shaded area. Each curve corresponds to the bound indicated in (d) and (f).

bound from Λ_c in $e^+e^-\to e^+e^-$, that from $p\bar{p}\to e^+e^-+\cdots$, and the kinematical bound from $\Delta\geq 0$ with Δ in (8), which imposes no essential lower bound on M_X. The allowed values of $R(60\text{ GeV})$, $R(M_Z)$, and Γ_Z deviate from their standard-model values. The singlet gluon with 170 to 300 GeV can increase $R(60\text{ GeV})$, which possibly explains the (slight) enchancement in R at TRISTAN.[31] The singlet gluon (heavy photon) decreases (increases) $R(M_Z)$, and increases (decreases) γ_Z. Although the larger $R(M_z)$ and the smaller Γ_Z of the heavy photon near $M_X=M_Z$ are already ruled out by the SLC[22] and LEP[23] data, the rest regions as well as the whole regions of the singlet gluon still remain consistent within errors. More precise measurements in the near future should be able to distinguish the present model from the standard model. We hope that these predictions are examined in the forthcoming experiments at TRISTAN, SLC, and LEP.

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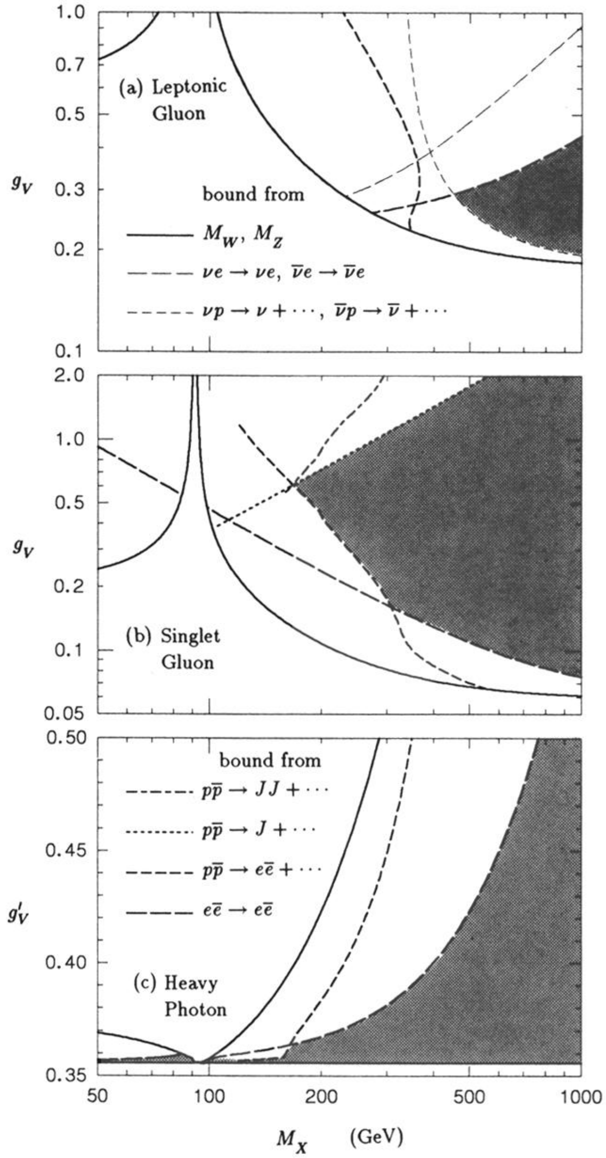

FIG. 1. The experimental bounds on g_V (or g'_V) vs M_X for (a) leptonic gluon, (b) color-singlet gluon, and (c) heavy photon. The allowed regions are indicated by the shaded area. Each curve corresponds to the bound indicated in (a) and (c).

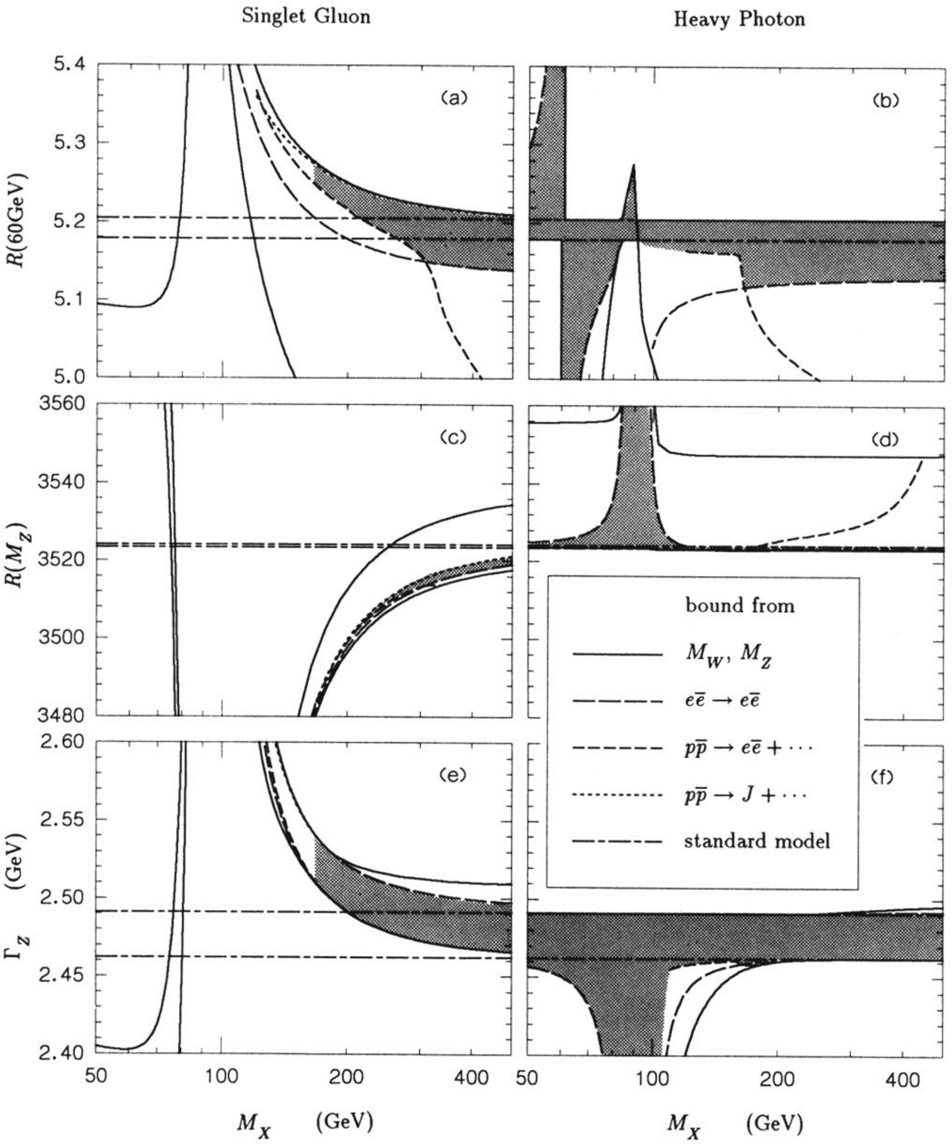

FIG. 2. The experimental bounds on $R(60\text{ GeV})$ [(a) and (b)], $R(M_Z)$ [(c) and (d)], and Γ_Z [(e) and (f)] vs M_X for the singlet gluon [(a), (c), and (e)] and for the heavy photon [(b), (d) and (f)]. The allowed regions are indicated by the shaded area. Each curve corresponds to the bound indicated in (d) and (f).