Extra Weak Bosons Implied by Complementarity in a Confining Gauge Theory

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Abstract

Extra W and Z bosons together with W and Z as composite particles are introduced in a confining gauge model based on a "color" $SU(2)_L^{loc} \times SU(2)_L^{loc} \times SU(2)_R^{loc}$ symmetry. Within the framework of complementarity, the vector meson (such as Z) dominance of the photon is naturally implemented and quarks (q_i^A for A=1,2,3 and i=1,2) and leptons (ℓ_i) are composites of scalars, $\tilde{w}_i$, carrying the weak charge and spinors, c^α (α = 0,1,2,3), carrying the three colors (α = 1,2,3) and the lepton number ($\alpha = 0$): $q_i^A \sim \tilde{w}_i c^A$ and $\ell_i \sim \tilde{w}_i c^0$. The confined gauge model is shown to be equivalent to the conventional model realized in the Higgs phase as far as the scalar degrees of freedom are frozen. Phenomenological implications of these extra W and Z bosons are discussed.

The experimental determination of m_W = (80.00 ± 0.56) GeV[1] and m_Z = (91.09 ± 0.06) GeV[2] has confirmed the mass relation, $m_W = \cos\theta m_Z$, with $\sin\theta$ evaluated in low - energy weak interactions.[3] It has implied the validity of the standard electroweak model of the Glashow - Weinberg - Salam (GWS) type[4] based on $SU(2)_L^{loc} \times U(1)_Y^{loc}$. However, there is a theoretical belief that new physics beyond the standard model manifests itself above the energy scale specified by the Fermi mass, $G_F^{-1/2}$, of ~300 GeV. Among them are new phenomena due to compositeness of the "elementary" particles such as quarks, leptons and weak bosons.[5] If underlying dynamics for composite particles are provided by a non - abelian gauge theory, the useful notion called complementarity[6] can be used to examine low - energy physics for composites.[7] When it is applied to weak bosons, the GWS model turns out to be (almost) equivalent to the model on $U(1)_{em}^{loc}$ with the confined "color" $SU(2)_L^{loc}$ symmetry, *i.e.*, the Bjorken-Hung-Sakurai (BHS) model for the kinetic γ - Z mixing scheme.[8] The weak bosons, $W^\pm$ and Z, are made as[9] $W_\mu^\pm \sim Tr(\tau^{(\pm)}\tilde{w}_L^\dagger D_\mu \tilde{w}_L)$ and $Z_\mu \sim Tr(\tau^{(3)}\tilde{w}_L^\dagger D_\mu \tilde{w}_L)$, where $\tilde{w}_L$ is a scalar carrying the weak charge and is represented by the Higgs scalar ϕ as $\tilde{w}_L = (\phi^G, \phi)$. At the same time, L-handed quarks (q_{Li}^A for A=1,2,3 and i=1,2) and leptons (ℓ_{Li}) are regarded as composites described by $q_{Li}^A = \tilde{w}_{Li}^a c_{La}^A$ and $\ell_{Li} = \tilde{w}_{Li}^a c_{La}^0$. Starting with the lagrangian of the GWS model, one can derive the BHS model with the kinetic mixing parameter, λ, for γ - Z, $\lambda = e/g$ under the constraint of $\langle \tilde{w}_L^\dagger \tilde{w}_L \rangle = I$.[10] This equality can be regarded as a result of vector meson (such as Z) dominance of the photon.[11]

One may wonder what happens in QCD, which is certainly based on the confining color $SU(3)_c^{loc}$ symmetry. Nucleons, scalar mesons and vector mesons are composites of quarks. Complementarity will state that composite nucleons are regarded as (constituent) quarks and composite vector mesons as massive gluons.[12] Scalar mesons are described by the Nambu - Goldstone bosons, which are not absorbed into the massless gluons. Let the flavor group be $SU(3)_f$ for q_A^i (A =1, 2, 3 for three colors; i = 1, 2, 3 for three flavors), *i.e.*, u, d and s, which comes from the symmetry breaking of the chiral $SU(3)_L \times SU(3)_R$ symmetry. To faciliate the symmetry breaking, we introduce two scalars, ξ_{Li}^A: $(\mathbf{3}, \mathbf{1})$ and ξ_{Ri}^A: $(\mathbf{1}, \mathbf{3})$ for $(SU(3)_L, SU(3)_R)$, which are decomposed as $\xi_{Li}^A = \xi_i^j \xi_{Vj}^A$ and $\xi_{Ri}^A = \xi_i^{\dagger j} \xi_{Vj}^A$. It is suggested that ξ_V is identified with scalar diquarks, $\xi_{Vi}^A = \varepsilon^{ABC} \varepsilon_{ijk} q_B^j q_C^k / f_\Pi^2$.[12] The remaining scalar, ξ, represents the Nambu - Goldstone modes, Π_i^j as $\xi = \exp(\Pi/f_\Pi)$. QCD gets broken completely as fas as diquarks are condensed to develop $< \xi_{Vi}^A > = f_\Pi \delta_i^A$. In this phase, *i.e.*, the Higgs phase of QCD, the gluons, G_A^B, become massive and serve as the octet vector mesons including ρ and quarks act as the octet baryons including P, N and Λ. While, in the confining phase, color-singlet composites are supplied by $\xi_{Vi}^A q_A^j / f_\Pi$ ($\sim qqq$ for $\xi_V \sim qq$) as the octet baryons and by $\xi_V^\dagger i D_\mu \xi_V / f_\Pi^2$ ($\sim \bar{q}\bar{q}qq$) as the octet vector mesons. Then, the both phases at low-energies contain the octet baryons and vector mesons. The transmutation of gauge bosons (*i.e.*, gluons) into massive vector mesons (*i.e.*, ρ etc.) arises.[13] The similar suggestion has been lately advocated on the basis of the non-linear sigma model with a dummy hidden symmetry,[14] where gauge bosons are regarded as composites and scalar mesons like π are taken into account but without the baryons as qqq.

Along this line of the compositeness of "elementary" particles, a possible new physics beyond the standard model is investigated by introducing extra W and Z bosons. The confining "color" gauge group to be studied in the present article is specified by $SU(2)_L^{loc}$ for the W and Z bosons as well as $G^{loc} = SU(2)_V^{loc} \times SU(2)_A^{loc}$ (equivalently, $SU(2)_L^{loc} \times SU(2)_R^{loc}$) for extra W and Z bosons. The QCD - like "color" (vectorial) $SU(2)_V^{loc}$ symmetry as G^{loc} is not suitable for the L - R asymmetric weak interactions. If the effects from the composite vector mesons coupled to the right - handed currents (corresponding to the $SU(2)_R^{loc}$ - gauge bosons) are neglected, the extra W and Z bosons, related to $SU(2)_L^{loc}$, are allowed to be as light as 100 GeV as far as the low-energy weak interaction phenomenology is concerned.[15] It is because the couplings to quarks and leptons are of the V - A form, which does not alter low-energy charged-current interactions. The lagrangian with extra composite weak bosons is characterized by vector meson dominances, which are described by the kinetic mixing terms among the photon (A^0), W and Z (mainly V) and extra W and Z (mainly L and R)[16]

$$\mathcal{L}_{mix} = -\frac{1}{2}(\lambda_{\gamma V} V_{\mu\nu}^{(3)} + \lambda_{\gamma L} L_{\mu\nu}^{(3)} + \lambda_{\gamma R} R_{\mu\nu}^{(3)}) A^{0\mu\nu} - \frac{\lambda_{VL}}{2} L_{\mu\nu}^{(i)} V^{(i)\mu\nu} \qquad (3 \cdot 9)$$

We will demonstrate how the kinetic mixings are generated in the confining phase of $SU(2)_L^{loc} \times \mathcal{SU}(2)_L^{loc} \times \mathcal{SU}(2)_R^{loc} (\equiv \mathcal{G}^{loc})$ and obtain the effective lagrangian for composite quarks, leptons, W, Z and extra weak bosons.[17)]

The particles contained are 1) "color" gauge bosons, $(G_\mu)_a^b$ of $SU(2)_L^{loc}$ with the gauge coupling g, $(G_{L\mu})_m^n$ of $\mathcal{SU}(2)_L^{loc}$ with g_L and $(G_{R\mu})_m^n$ of $\mathcal{SU}(2)_R^{loc}$ with g_R, and a "flavor" gauge boson, B_μ, of $U(1)_Y^{loc}$ with g'; 2) "color" $\mathcal{SU}(2)_{L,R}$ doublet fermions with the "flavor" suffix α (= 0,1,2,3) for the three colors (α = 1,2,3) and the lepton number ($\alpha = 0$), c_{mL}^α: (**1**, Y; **2**, **1**) and c_{mR}^α: (**1**, Y; **1**, **2**), for ($SU(2)_L^{loc}$, $U(1)_Y^{loc}$; $\mathcal{SU}(2)_L^{loc}$, $\mathcal{SU}(2)_R^{loc}$), where m(= 1, 2) denotes the $\mathcal{SU}(2)_{L,R}^{loc}$ - "color" and Y (= B -L)= -1 for c^0; = 1/3 for c^A (A = 1, 2, 3),and; 3) three kinds of "color" scalars, $\tilde{w}_{Li}^m$: (**1**, $\tau^{(3)}$; **2**, **1**), $\tilde{w}_{Ri}^m$: (**1**, $\tau^{(3)}$; **1**, **2**) and ξ_m^a: (**2**, 0; **2**, **1**), where i(= 1,2) and a(= 1,2), respectively, denote the "flavor" and $SU(2)_L^{loc}$ - "color".

Let us demand that $\mathcal{G}^{loc}$ be confined to generate composite particles and to form the following scalar condensates: $\langle \tilde{w}_{L(R)i}^m (\tilde{w}_{L(R)}^\dagger)_m^j \rangle = \delta_i^j$, $\langle (\tilde{w}_{L(R)}^\dagger)_m^i \tilde{w}_{L(R)i}^n \rangle = \delta_m^n$, $\langle (\xi^\dagger)_a^m \xi_m^b \rangle = \delta_a^b$ and $\langle \xi_m^a (\xi^\dagger)_a^n \rangle = \delta_m^n$. Also defined are "color" - singlet composite fermions for quarks (q) and leptons (ℓ) and composite vector mesons, V_μ, L_μ and R_μ for W, Z and extra weak bosons, according to:

$$q_{iL}^A = \sum_m \tilde{w}_{Li}^m c_{mL}^A, \qquad \ell_{iL} = \sum_m \tilde{w}_{Li}^m c_{mL}^0, \qquad (2a, b)$$

$$q_{iR}^A = \sum_m \tilde{w}_{Ri}^m c_{mR}^A, \qquad \ell_{iR} = \sum_m \tilde{w}_{Ri}^m c_{mR}^0, \qquad (2c, d)$$

$$f(V_\mu)_i^j = (\tilde{w}_L i D_\mu \tilde{w}_L^\dagger)_i^j, \quad f_L(L_\mu)_i^j = [\tilde{w}_L(\xi i D_\mu \xi^\dagger)\tilde{w}_L^\dagger]_i^j, \qquad (2e, f)$$

$$f_R(R_\mu)_i^j = (\tilde{w}_R i D_\mu \tilde{w}_R^\dagger)_i^j \qquad (2g)$$

as well as $f' A_\mu^0 = g' B_\mu$. Hereafter, quarks and leptons are denoted by $\psi_{iL}^\alpha = \ell_{iL}$ (α=0); $= q_{iL}^A$ (α (=A) = 1,2,3).

By noticing that $gG_{\mu\nu} = (\tilde{w}_L\xi)^\dagger v_{1\mu\nu}(\tilde{w}_L\xi)$, $g_L G_{L\mu\nu} = \tilde{w}_L^\dagger v_{2\mu\nu}\tilde{w}_L$ and $g_R G_{R\mu\nu} = \tilde{w}_R^\dagger v_{3\mu\nu}\tilde{w}_R$ for $v_{\mu\nu} = \partial_\mu v_\nu$ - $\partial_\nu v_\mu$ - $i[v_\mu, v_\nu]$ etc., where

$$v_{1\mu} = fV_\mu + f_L L_\mu + e(\tau^{(3)}/2)A_\mu^0, \qquad (3a)$$

$$v_{2\mu} = fV_\mu + e(\tau^{(3)}/2)A_\mu^0, \qquad (3b)$$

$$v_{3\mu} = f_R R_\mu + e(\tau^{(3)}/2)A_\mu^0, \qquad (3c)$$

we find, from the lagrangian for the gauge theory evaluated in the confining phase,[18)] $\mathcal{L}_{conf}$ to be:

$$\mathcal{L}_{conf} = -\frac{1}{2g^2}Tr(v_{1\mu\nu}v_1^{\mu\nu}) - \frac{1}{2g_L^2}Tr(v_{2\mu\nu}v_2^{\mu\nu}) - \frac{1}{2g_R^2}Tr(v_{3\mu\nu}v_3^{\nu\mu})$$

$$
\begin{aligned}
&-\frac{e^2}{4g'^2}A^0_{\mu\nu}A^{0\mu\nu}+\Lambda^2Tr(fV_\mu)^2+\Lambda_L^2Tr(f_LL_\mu)^2+\Lambda_R^2Tr(f_RR_\mu)^2,\\
&+\overline{\psi_L}\gamma^\mu(i\partial_\mu+fV_\mu+eQ_{em}A^0_\mu)\psi_L+\overline{\psi_R}\gamma^\mu(i\partial_\mu+f_RR_\mu\\
&+eQ_{em}A^0_\mu)\psi_R,
\end{aligned}
\tag{4}
$$

as long as the radial scalar excitations are neglected. The mass - dimensions, Λ and $\Lambda_{L(R)}$, are associated with the scalars, $\tilde{w}_L$ and $\xi(\tilde{w}_R)$. Note that the extra boson, L_μ, does not couple to quarks and leptons. The coupling strengths, f, f_L, f_R and f', satisfy $1/f^2 = 1/g^2 + 1/g_L^2$, $f_L = g$, $f_R = g_R$ and $1/f'^2 = 1/g^2 + 1/g'^2 + 1/g_L^2 + 1/g_R^2$ for the canonical kinetic terms of V_μ, L_μ, R_μ and A^0_μ. For "color" singlet composites, the unbroken $U(1)^{loc}_Y$ symmetry is coincident with the $U(1)^{loc}_{em}$ symmetry. The third - isospin is provided through the $U(1)^{loc}_Y$ charge of $\tilde{w}$, which ensures $Q_{em} = (\tau^{(3)}+Y)/2$.The kinetic mixings are now characterized by e/f ($=\lambda_{\gamma V}$) for A^0 and V, $e/f_{L(orR)}$ ($=\lambda_{\gamma L(orR)}$) for A^0 and L (or R) and f/f_L ($=\lambda_{VL}$) for V and L. The kinetic mixings cause the following field - redefinition:

$$
\mathcal{V}^{(3)}_\mu=\sqrt{1-\lambda^2_{\gamma V}}(V^{(3)}_\mu+\lambda_{VL}L^{(3)}_\mu-\frac{\lambda_{\gamma V}\lambda_{\gamma R}}{1-\lambda^2_{\gamma V}}R^{(3)}_\mu), \tag{5a}
$$

$$
\mathcal{V}^{(\pm)}_\mu=V^{(\pm)}_\mu+\lambda_{VL}L^{(\pm)}_\mu,\quad \mathcal{L}^{(i)}_\mu=\sqrt{1-\lambda^2_{VL}}L^{(i)}_\mu, \tag{5b, c}
$$

$$
\mathcal{R}^{(3)}_\mu=\sqrt{(1-\lambda^2_{\gamma V}-\lambda^2_{\gamma R})/(1-\lambda^2_{\gamma V})}R^{(3)}_\mu,\quad \mathcal{R}^{(\pm)}_\mu=R^{(\pm)}_\mu. \tag{5d, e}
$$

It is not difficult to show the equivalence of the interactions in the confining and Higgs phase as far as the scalar degrees freedom are frozen. The vector fields, A_μ, $\mathcal{V}_\mu$, $\mathcal{L}_\mu$ and $\mathcal{R}_\mu$, defined in Eqs.(5a $\sim$ e), are also expressive in terms of fields with the orthogonal mixings in the Higgs phase, which reflect $SU(2)^{loc}_L\times \mathcal{SU}(2)^{loc}_L - SU(2)^{loc}_D$ with the gauge coupling $g_D = gg_L/\sqrt{g^2+g_L^2}$ ($=g\cos\theta_L = g_L\sin\theta_L$), $U(1)_Y\times \mathcal{SU}(2)^{loc}_R \to U(1)^{loc}_D$ with $g'_D = g'g_R/\sqrt{g'^2+g_R^2}$ ($=g'\cos\theta_R = g_R\sin\theta_R$) and $SU(2)^{loc}_D\times U(1)^{loc}_D \to U(1)^{loc}_{em}$ with $e = g_Dg'_D/\sqrt{g_D^2+g'^2_D}$ ($=g'_D\cos\theta = g_D\sin\theta$):

$$
A_\mu=\sin\theta a^{(3)}_\mu+\cos\theta b_\mu,\quad \mathcal{V}^{(3)}_\mu=\cos\theta a^{(3)}_\mu-\sin\theta b_\mu, \tag{6a, b}
$$

$$
\begin{aligned}
&\mathcal{V}^{(\pm)}_\mu=\sin\theta_LG^{(\pm)}_{L\mu}+\cos\theta_LG^{(\pm)}_\mu,\quad \mathcal{L}^{(i)}_\mu=\cos\theta_LG^{(i)}_{L\mu}-\sin\theta_LG^{(i)}_\mu,\\
&\mathcal{R}^{(3)}_\mu=\cos\theta_RG^{(3)}_{R\mu}-\sin\theta_RB_\mu,\quad \mathcal{R}^{(\pm)}_\mu=G^{(\pm)}_{R\mu},
\end{aligned}
\tag{6c $\sim$ f}
$$

where $a^{(3)}_\mu = \sin\theta_LG^{(3)}_{L\mu} + \cos\theta_LG^{(3)}_\mu$ and $b_\mu = \sin\theta_RG^{(3)}_{R\mu} + \cos\theta_RB_\mu$. Following these relations together with the identification of $f = g_D$, $f_L = g$ and $f_R = g_R$ leading to

$\lambda_{\gamma V} = \sin\theta$, $\lambda_{\gamma L} = \sin\theta\sin\theta_L$, $\lambda_{\gamma R} = \cos\theta\sin\theta_R$ and $\lambda_{VL} = \sin\theta_L$, it is shown that the lagrangian evaluated in the Higgs phase is exactly same as the one in the confining phase, $\mathcal{L}^A_{conf}$. The similar argument can be applied to models with an extra Z bosons based on $\mathcal{G}^{loc} = SU(2)^{loc}_L \times U(1)^{loc}$.[19]

For the $SU(2)^{loc}_L \times U(1)^{loc}_Y \times \mathcal{SU}(2)^{loc}_L$ model, where the contribution from the right - handed bosons, R_μ, are neglected, we find that the low - energy phenomenology is controlled by

$$\mathcal{L}^{ch}_{eff} = 2\sqrt{2}G_F J^{(-)}_{L\mu} J^{(+)\mu}_L, \tag{7a}$$
$$\mathcal{L}^{n}_{eff} = 4\sqrt{2}G_F[(J^{(3)}_L - \sin^2\theta J^{em})^2 + C_{em}J^{em}J^{em}], \tag{7b}$$

where $4\sqrt{2}G_F m_V^2 = f^2$ for $m_V = f\Lambda$ and $C_{em} = (m_V^2/m_L^2(f^2/f_L^2)\sin^4\theta$. The weak boson masses, $m_{W,Z}$, are fixed to be: $m_Z = 91.09$ GeV (as the central value of the averaged data) The constraints on $\sin^2\theta$ and C_{em}, respectively, come from ν - induced reactions[20] and the Bhabha - scattering with $\Lambda^c_- > 7.1$ TeV (for vector coupling),[21] which result in $\sin^2\theta = (0.22 \sim 0.24)$ and $C_{em} < 0.002$. Computation of C_{em} shows that $C_{em} < 0.002$ is satisfied. Another constraints are based on the experimental results on $p\bar{p} - W'$ (or Z') $+\cdots$ followed by W' (Z') $- e\nu$ (e^+e^-).[22] These impose $m_{W'} \gtrsim$ (290, 240, 200) GeV for $\sin^2\theta = (0.22, 0.2225, 0.2235)$ and $m_{Z'} \gtrsim$ (440, 330, 200) GeV for $\sin^2\theta = (0.22, 0.225, 0.228)$ but no restriction for the case with $\sin^2\theta \gtrsim 0.2235$ (W') and 0.228 (Z'). The prediction on $p\bar{p} - W'$ (or Z') $+\cdots - jj + \cdots$ is so far consistent with the data.[23] The theoretical constraint dectates $m_W m_{W'} = \cos\theta m_Z m_{Z'}$. Under these constraints, we evaluate various quantities and show

1) the dependence of the Z decay widths on $m_{Z'}$ ($= m_{Z*}$ in the Figures) for $\sin^2\theta =$ 0.22, 0.225 and 0.23: $\Gamma(Z \to \text{all})$ (in *Fig*.1) and $\Gamma(Z \to e^+e^-)$ (in *Fig*.2) together with the standard model predictions at $\sin^2\theta = 0.2313$ (for $m_t = 100$ GeV),
2) the coupling constant of f_L ($= g^*$ in the Figure) divided by e (in *Fig*.3) and the Z' decay width $\Gamma(Z' \to \text{all})$ (in *Fig*.4) and
3) the cross section of $\sigma(e^+e^- \to \mu^+\mu^-)$ as functions of $\sqrt{s}$ for $m_{Z'} = 250$, 500, 1000, 1500, 2000 and 3000 GeV at $\sin^2\theta = 0.225$ (in *Fig*.5).

The expected deviations are to be detected by the precise determination of the Z properties. Furthermore, TeV - e^+e^- colliders such as JLC, CLIC and so on will see the extra weak boson as heavy as 1 TeV or even heavier than the beam energy owing to the broader width of Z' of $\mathcal{O}(100$ GeV) as long as the extra boson acts as a "elementary" particle. However, since the compositeness scale can be as low as the order of $G_F^{-1/2} \cong$ 300 GeV, the electron itself will manifest the substructure perhaps through (unknown) form - factor effects around $E = \mathcal{O}(1$ TeV), which even distort the behavior of e^+e^- annihilation via the photon and Z.

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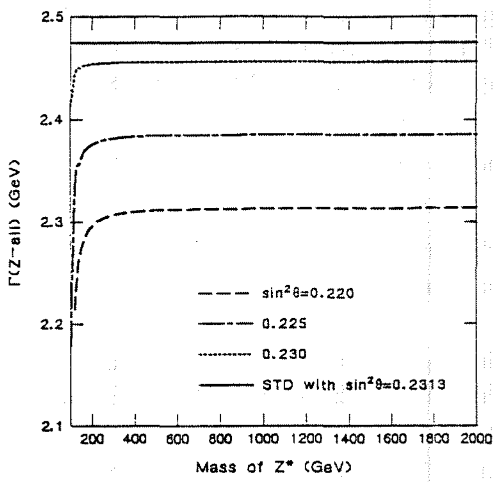

Figure 1

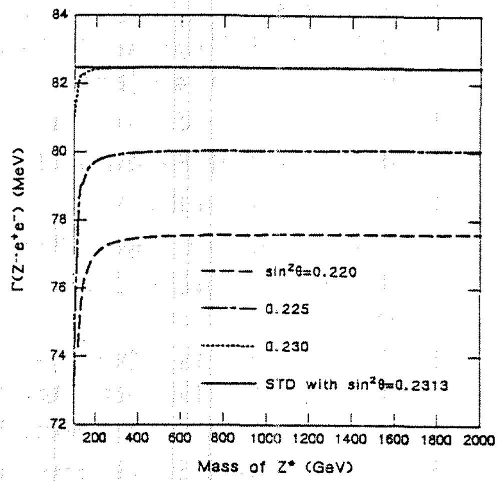

Figure 2

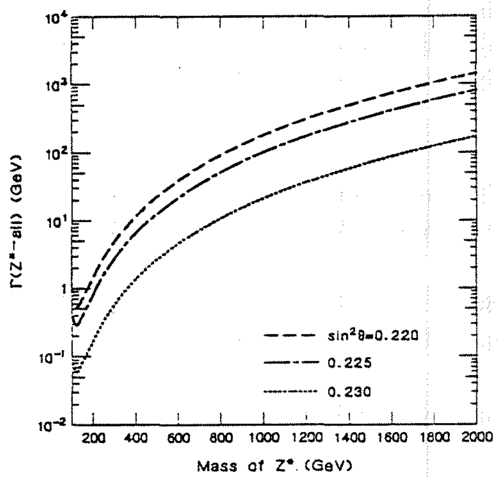

Figure 3

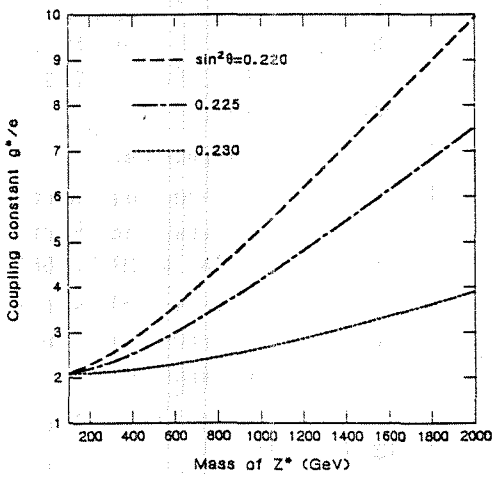

Figure 4

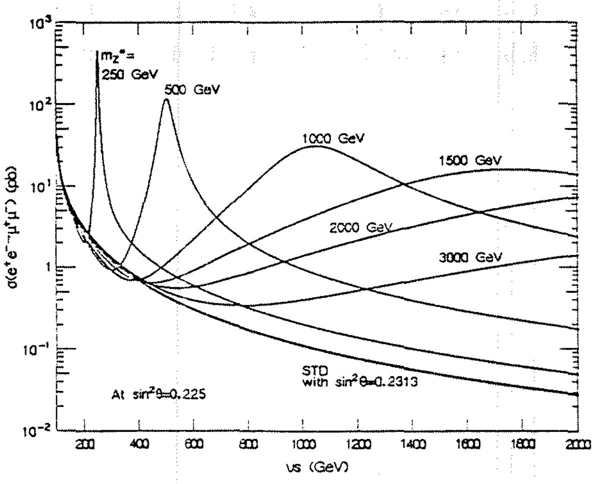

Figure 5