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SEARCH FOR NEW NEUTRAL BOSONS AT FUTURE COLLIDERS*

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This is a short review of present and future limits on new neutral gauge bosons, in particular on hadrophilic or leptophobic Z's recently proposed to interpret the observed fluctuations of $\Gamma_{c,b}$ at LEP. Light gauge bosons coupled to lepton number differences or to baryon number are also examples of the model dependence of these bounds. The mixing between the U(1) factors plays an important role in the phenomenology of these extended electroweak models. Future improvements based on the analysis of precise electroweak data are emphasized.

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1. Introduction

There is a large literature on new weak interactions and their limits. For recent reviews on the discovery and identification of extra gauge bosons see Ref. [1, 2]. (See Refs. [3, 4] for earlier reports.)

Up to now there is no compelling evidence for a new Z'. On the contrary the standard model (SM) is in agreement with present data [5–7], although the observed fluctuations in the charm and bottom Z widths, $\Gamma_{c,b}$, at LEP have led to speculate on the possibility of a new hadrophilic or leptophobic gauge boson [2, 8]. At any rate many extensions of the SM predict new gauge bosons. As on the other hand present limits on new interactions are rather weak and very model dependent, it is interesting to study the possibility of their discovery at future colliders and to compare the Z' physics potential of the different machines.

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We present a short review of five topics. Present [7, 8] and future [1, 2] Z' limits are discussed in Section 2, including the hadrophilic or leptophobic models proposed to explain the $\Gamma_{c,b}$ deviations. In order to further show the model dependence of these bounds, in Section 3 we give two examples of extra interactions with gauge boson masses $M_{Z'}$ near or below the Z mass. These models, which are interesting by themselves, gauge lepton number differences [9] and baryon number [10], respectively. The latter is also hadrophilic or leptophobic but it has not the correct charge assignments to accommodate the observed fluctuations of $\Gamma_{c,b}$. The mixing between the abelian subgroups $U(1)_Y$ and $U(1)_B$, which plays a major role in the phenomenology of the model, is studied in some detail [11]. Finally, in Section 4 we revise the effects of radiative corrections in models with an extra U(1) factor [12].

2. Z' limits

An extra abelian gauge interaction is parametrized by the mass of the new gauge boson Z', $M_{Z'}$, its mixing with the standard Z^0 boson, θ_3 ($= -\phi, -\theta$ in Refs. [1, 7], respectively), and its couplings with the known fermions. (If the model requires extra matter there are more (Z') couplings whose effects on the processes involving the observed fermions are mainly encoded in the total Z' width, $\Gamma_{Z'}$.) Many of these parameters must be fixed when comparing with experiment in order to obtain sensible results. The ${Z^0}'$ couplings are usually fixed, leaving the Z' mass (and the $Z'Z^0$ mixing angle) free. Thus, limits are only quoted for definite models, being very model dependent.

2.1 Present Z' limits

Present bounds come from lepton pair production at TEVATRON (direct) and from precise electroweak data (indirect). These constraints are usually illustrated giving the limits for five specific models, χ, ψ, η, LR, SSM. The χ, ψ, η, LR models can be embedded in E_6, whereas the SSM model assumes a new gauge boson with the same couplings as but heavier than the standard Z^0. We collect in Table I the bounds on $M_{Z'}$ for these models (see Refs. [1, 7]). The integrated luminosity at TEVATRON is 19.6 pb^{-1} (lepton pairs include $e^+e^-, \mu^+\mu^-$) and the global electroweak analysis (requiring 95% C.L.) includes the 1993 LEP data. The constrained limits correspond to minimal Higgs contents. The direct bounds will improve with the integrated luminosity at TEVATRON. If no signal is observed for 70 pb^{-1}, the limits will increase $\sim$ 120 GeV [1, 13]. All these limits are obtained assuming that the new gauge boson can only decay into known fermions. If the open channels include the three complete E_6 supersymmetric families, the $M_{Z'}$ limits are reduced by $50 - 100$ GeV, depending on the model [1, 13]. The indirect bounds will improve slightly when all LEP data are analysed. This is assuming that no significative departure from the SM is found.

TABLE I

Present $M_{Z'}$ limits (in GeV) for typical models.

Direct	Indirect (unconstrained)	Indirect (constrained)	
χ	425	330	920
ψ	415	170	170
η	440	220	610
LR	445	390	1360
SSM	505	960	

At present there are fluctuations in $\Gamma_{c,b}$ at LEP. The models above do not explain these fluctuations. However with a different choice of Z' charges this departure from the SM can be related to the existence of a new gauge boson. Several groups have discussed this possibility recently [8]. The new Z' must couple only to quarks (hadrophilic) for the Z couplings to leptons are in very good agreement with the SM values. In the first two papers of Ref. [8] the new quark charge ratios are fixed to accommodate the $\Gamma_{c,b}$ fluctuations; whereas in the third one it is pointed out that the unique U(1) in E_6 with zero lepton charges (leptophobic), $Y_\eta + \frac{1}{3}Y$ [14] ($Y_\eta = -Y'$ in this reference), can be effective at the electroweak scale if the necessary $\mathrm{U}(1)_Y \times \mathrm{U}(1)_\eta$ mixing is generated when renormalizing the gauge couplings down to low energies. As a matter of fact this relatively large mixing can be obtained for a definite matter content. The quark couplings also explain the observed $\Gamma_{c,b}$ deviations.

2.2 Future Z' limits

At future colliders the Z' limits will improve if no departure from the SM predictions is observed. In Table II we gather the expected bounds at present and future colliders. A large part of the detailed discussion of how to derive these bounds is presented in Ref. [1] (see also Ref. [15]), and we refer the interested reader to this review.

TABLE II

$M_{Z'}$ limits (in GeV) for typical models at future colliders. TEVATRON ($p\bar{p}$ at $\sqrt{s} = 1.8$ TeV, $\mathcal{L}_{\rm int} = 1\ fb^{-1}$), LEP200 ($e^+e^-$ at $\sqrt{s} = 0.2\ TeV$, $\mathcal{L}_{\rm int} = 0.5\ fb^{-1}$) and HERA ($ep$ at $\sqrt{s} = 0.314$ TeV, $\mathcal{L}_{\rm int} = 0.6\ fb^{-1}$) provide a modest improvement compared to LHC (pp at $\sqrt{s} = 10$ TeV, $\mathcal{L}_{\rm int} = 40\ fb^{-1}$) and NLC ($e^+e^-$ at $\sqrt{s} = 0.5$ TeV, $\mathcal{L}_{\rm int} = 50\ fb^{-1}$).

Collider	TEVATRON	LHC	LEP200	NLC	HERA
χ	775	3040	695	3340	235
ψ	775	2910	269	978	125
η	795	2980	431	1990	215
LR	825	3150	493	2560	495

3. Leptonic and baryonic extended gauge models

In this Section we discuss two classes of models which evade the usual $M_{Z'}$ limits. In both cases $M_{Z'}$ can be smaller than M_Z. One simplifying but strong assumption in many analyses is that the extra interaction is universal. Below we comment on models gauging lepton number differences as examples of non-universal interactions. The class of models gauging baryon number is also reviewed. This interaction is universal but provides an example of models where the mixing between U(1) factors is phenomenologically relevant. The leptophobic model $Y_\eta + \frac{1}{3}Y$ above is another example of hadrophilic model evading usual $M_{Z'}$ bounds.

3.1 Lepton number difference extensions

These models result from requiring that the extra U(1) be anomaly free without adding new fermions. The lepton number differences, $L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$, are the only solutions [9], up to fermion mixing [16]. Quark charges are zero. The constraints on these models are not very stringent, obviously it is difficult to constrain $L_\mu - L_\tau$. e^+e^- colliders constrain the other two lepton differences. For example LEP can set a bound on the $L_e - L_\tau$ gauge boson mass $\sim 130\frac{g'}{e}$ GeV [17].

3.2 Baryon number gauge models

The experimental limits on extra interactions involving only quarks are somewhat weak. A class of models with a new Z' coupling only to baryon number is phenomenologically allowed, even if $M_{Z'} < M_Z$ and the new gauge coupling strength is order 1 [10]. This extra Z' couples universally to the three known families but the matter content of the model is enlarged with heavy fermions to render the model anomaly-free. Although the Z' couplings to leptons are zero at tree level, small couplings are generated at higher orders. As a matter of fact it is the non-vanishing of these couplings what may allow for observing this new gauge boson in the dilepton channel at large hadron colliders. The origin of these small couplings is the mixing of the abelian kinetic terms.

Let us discuss this mixing more carefully for it is one example of the general case examined below. In the absence of a symmetry, all U(1) factors of a gauge group mix at some order in perturbation theory [12]. This mixing may be required in order to renormalize the theory or can be generated at higher orders as in this class of models. The new contribution can be written as an off-diagonal kinetic term which mixes the U(1) gauge fields or in a canonical way, redefining the gauge fields in order to keep their kinetic terms diagonal and conventionally normalized. In the latter case the mixing appears in the Z' current, which is modified by the addition of a mixing term proportional to the standard abelian current.

Thus, if $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_B$ is unbroken, the new effects can be taken into account by adding an off-diagonal kinetic term to the canonical lagrangian for the U(1) fields

$$\mathcal{L}_{kin} = -\tfrac{1}{4}\left(F^Y_{\mu\nu}F^{Y\mu\nu} + 2cF^Y_{\mu\nu}F^{B\mu\nu} + F^B_{\mu\nu}F^{B\mu\nu}\right) , \qquad (1)$$

with c a calculable quantity obtained by evolving the gauge couplings down to the electroweak scale. This lagrangian is equivalent to a canonical one with gauge fields

$$\begin{pmatrix} A'^Y \\ A'^B \end{pmatrix} = \begin{pmatrix} 1 & c \\ 0 & \sqrt{1-c^2} \end{pmatrix} \begin{pmatrix} A^Y \\ A^B \end{pmatrix} , \qquad (2)$$

and covariant derivatives

$$D_\mu f_i = \partial_\mu f_i + i(\tilde{q}_i'^Y \; \tilde{q}_i'^B) \begin{pmatrix} A'^Y_\mu \\ A'^B_\mu \end{pmatrix} f_i , \qquad (3)$$

where f_i is a matter field with gauge couplings

$$\begin{aligned}(\tilde{q}_i'^Y \; \tilde{q}_i'^B) &= (q_i^Y \; q_i^B) \begin{pmatrix} g^Y & 0 \\ 0 & g^B \end{pmatrix} \begin{pmatrix} 1 & -\frac{c}{\sqrt{1-c^2}} \\ 0 & \frac{1}{\sqrt{1-c^2}} \end{pmatrix} \\ &= (q_i^Y \; q_i^B) \begin{pmatrix} g^Y & -\frac{g^Y c}{\sqrt{1-c^2}} \\ 0 & \frac{g^B}{\sqrt{1-c^2}} \end{pmatrix} . \end{aligned} \qquad (4)$$

Hence, A'^{Y} will be identified with the hypercharge and A'^{B} with a new gauge boson with charges $\tilde{q}_i'^{B} = \frac{g^B}{\sqrt{1-c^2}} q_i^B - \frac{g^Y c}{\sqrt{1-c^2}} q_i^Y$. This modified charges include, as the only new effect, a mixing term proportional to the hypercharge. It is apparent from the second formulation that new physical effects will require the exchange of the new gauge boson (for in the unbroken case there is no mass mixing) and that they are at least suppressed by a factor c if they involve leptons, for which $q_i^B = 0$.

After spontaneous symmetry breaking the rotation which diagonalizes the vector boson mass matrix introduces off-diagonal kinetic terms for the photon $A_\mu^\gamma = c_W A_\mu^Y + s_W A_\mu^W$ and the standard model gauge boson $A_\mu^{Z^0} = -s_W A_\mu^Y + c_W A_\mu^W$ in the non-canonical lagrangian (see Eq. (1)),

$$\begin{aligned}\mathcal{L}_{kin} = &- \tfrac{1}{4}(F_{\mu\nu}^\gamma F^{\gamma\mu\nu} + F_{\mu\nu}^{Z^0} F^{Z^0\mu\nu} + 2cc_W F_{\mu\nu}^\gamma F^{B\mu\nu} \\ &- 2cs_W F_{\mu\nu}^{Z^0} F^{B\mu\nu} + F_{\mu\nu}^B F^{B\mu\nu}) ,\end{aligned} \tag{5}$$

with $s_W(c_W) = \sin\theta_W(\cos\theta_W)$ the electroweak mixing. In this basis the boson mass matrix is diagonal because the vev v giving a mass to A^B transforms trivially under $\mathrm{SU}(2)_L\times\mathrm{U}(1)_Y$ and the standard Higgs doublet has zero $\mathrm{U}(1)_B$ charge. However the eigenvalues are not the physical masses for the kinetic lagrangian is non-canonical. In the alternative formulation the lagrangian with canonical kinetic terms and a diagonal mass matrix has gauge couplings

$$\begin{aligned}(\tilde{q}_i^\gamma \tilde{q}_i^Z \tilde{q}_i^{Z'}) &= (q_i^W q_i^Y \;\; q_i^B) \begin{pmatrix} g^W & 0 & 0 \\ 0 & g^Y & -\frac{g^Y c}{\sqrt{1-c^2}} \\ 0 & 0 & \frac{g^B}{\sqrt{1-c^2}} \end{pmatrix} \\ &\times \begin{pmatrix} s_W & c_W & 0 \\ c_W & -s_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_3 & s_3 \\ 0 & -s_3 & c_3 \end{pmatrix} = (q_i^W q_i^Y \;\; q_i^B) \\ &\times \begin{pmatrix} e & \frac{ec_W}{s_W} c_3 & \frac{ec_W}{s_W} s_3 \\ \sqrt{\frac{5}{3}} e & \sqrt{\frac{5}{3}} \frac{e}{c_W} (-s_W c_3 + \frac{cs_3}{\sqrt{1-c^2}}) & \sqrt{\frac{5}{3}} \frac{e}{c_W} (-s_W s_3 - \frac{cc_3}{\sqrt{1-c^2}}) \\ 0 & -\frac{g^B s_3}{\sqrt{1-c^2}} & \frac{g^B c_3}{\sqrt{1-c^2}} \end{pmatrix} ,\end{aligned} \tag{6}$$

with

$$e = g^W s_W \quad and \quad s_W = \frac{\sqrt{3} g^Y}{\sqrt{3g^{Y2} + 5g^{W2}}} .$$

The $Z'Z^0$ mixing $s_3(c_3) = \sin\theta_3(\cos\theta_3)$ is a function of the gauge boson masses, $s_3 = sign(c)\sqrt{\frac{M^2_{Z^0}-M^2_Z}{M^2_{Z'}-M^2_Z}}$ [14].

The relevance of $c_\gamma = cc_W$ and $c_Z = -cs_W$ and the phenomenological signatures of the model are worked out in detail in Ref. [10]. In the canonical basis, with canonical kinetic lagrangian and physical vector boson masses, the standard model with an extra U(1) is in general described by a 3×3 gauge coupling matrix, product of a triangular matrix with zero WY and WB entries (as required by $SU(2)_L$ invariance) by the rotation matrix diagonalizing the gauge boson mass matrix, which only depends on two mixing angles, θ_W and θ_3. A non-zero θ_3 modifies the ρ parameter and the Z couplings to fermions [14].

4. Radiative corrections in extended electroweak models

Precise limits on the SM parameters are obtained comparing with one-loop expressions [18]. The corresponding equations for $SU(3)_C\times SU\ (2)_L\times U\ (1)_Y\times U\ (1)'$ have not been worked out. New one-loop corrections can be sometimes neglected. This approximation improves when the effective strength of the new force $\sim \frac{g'}{M_{Z'}}$ decreases. At any rate experiment allows only for small departures of the SM [5]. However, to obtain limits on new interactions new one-loop corrections would have to be included if the relevant range of Z' masses (couplings) is low (large) enough.

It is important in any case to use a general parametrization of the new interaction. This guarantees a consistent expansion in perturbation theory and justifies the use of approximate tree-level expressions in the fits [12, 19]. All new free parameters must be included in the analysis. Even if some are small (and generated by renormalization of the high energy couplings down to the electroweak scale). Two recent examples, where this is crucial, have been already discussed in the previous Sections. Both are related to the possible mixing between U(1) factors. In the leptophobic model in Section 2 [8] this mixing is essential to vanish the Z' couplings to leptons at the electroweak scale; whereas in the model gauging baryon number this mixing is responsible of the eventual observation of the new gauge boson in lepton pair production [10].

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