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NEW ISSUES IN Z' PHYSICS *

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ABSTRACT

We briefly review present bounds on extra gauge bosons. We also comment on new issues: *(i)* how to messure the mass of a new gauge boson at LEP, independently of its mixing with the Z^0; *(ii)* the use of rare decays as diagnostics for Z' gauge couplings at hadron colliders; *(iii)* the possibility of a negative contribution to the ρ parameter due to a strongly interacting extra $U(1)$; and *(iv)* the effect of fermion mixing on Z' fits.

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1. Introduction

Although the standard model with only the top and Higgs masses as unknown parameters is in very good agreement with experiment [1], there is no deep understanding of why the electroweak group is $SU(2)_L \times U(1)_Y$ or there are, for instance, three families. In fact there is no particular reason why there is not an extra $U(1)$ symmetry at the TeV scale. If so it would provide a new handle on grand unification [2] and/or superstring compactification [3]. In any case the new generation of large hadron colliders will test such a possibility. They will find or exclude new gauge bosons with masses up to 5 TeV, assuming they couple to quarks and leptons with gauge couplings of the usual size [4].

In Section 2 we review the experimental limits on new gauge interactions [5–11] and in Section 3 we comment on recent developments in Z' physics [12–15]. For reviews on the subject see Ref. [16].

2. Present Limits on New Gauge Interactions

At present there is no experimental evidence for a new Z' but only bounds on its interactions. These bounds come from accelerators (production or direct limits) and from precise electroweak data and astrophysics (indirect limits). They are model dependent, especially the latter. There are many gauge extensions of the standard model one can think of. We distinguish three types: models with universal couplings, models which couple differently to different families, and strong interacting models. In this Section we are only concerned with the first type. The $M_{Z'}$ bounds for non universal models are less stringent and very model dependent. For instance, an extra $U(1)$ coupling only to the electron minus the tau lepton number may exist and the corresponding gauge boson to have a mass slightly over 100 GeV [17]. New strong interactions are more uncertain. Of the universal type the E_6 models are the most popular ones. To illustrate present bounds we consider the usual models $Z_{\chi,\psi,\eta,LR,\chi'}$ (see Ref. [18] for definitions).

2.1 Direct Limits

In a recent analysis the CDF Collaboration has established a new limit for the integral e^-e^+ cross section above 200 GeV at $Tevatron$, $\sigma(200) < 1.31$ pb, excluding a new Z' with the same couplings as the standard Z^0 and a mass < 387 GeV at 95% $c.l.$ [19]. This bounds the $q\bar{q} \to \gamma, Z, Z' \to e^-e^+$ cross section for an arbitrary extra $U(1)$ and translates into the $M_{Z'}$ limits given in the first column of Table 1 [18]. The next generation of hadron colliders can improve these bounds up to ~ 5 TeV [4].

Table 1. Bounds on the mass of new gauge bosons (in GeV).

	direct	*indirect* (*unconstrained*)	*indirect* (*constrained*)
Z_χ	326	350	650
Z_ψ	330	290	620
Z_η	303	150	480
Z_{LR}	346	380	920
$Z_{\chi'}$	291	220	330

2.2 Indirect Limits

The limits from precise electroweak data on the mass of a new gauge boson are gathered in the second (third) column of Table 1 for unconstrained (constrained) models. Detailed analyses can be found in Refs. [5-9]. These limits bound the different ways a new Z' can contribute to low energy data. An extra gauge boson mixing with the standard Z^0 modifies the Z current

$$J_Z = cos\theta_3 J_{Z^0} - sin\theta_3 J_{Z'^0}, \tag{1}$$

as well as the Z mass

$$M_Z^2 = \frac{M_W^2}{c_W^2} + \frac{s_W^2 \gamma^2 \frac{M_W^4}{c_W^4}}{\frac{M_W^2}{c_W^2} - M_{Z'}^2}, \tag{2}$$

where

$$sin\theta_3 = \frac{s_W M_W^2 \gamma}{c_W^2 \sqrt{(M_{Z'}^2 - \frac{M_W^2}{c_W^2})(M_{Z'}^2 - M_Z^2)}}, \tag{3}$$

M_W is the W mass and $s_W = sin\theta_W$ with θ_W the electroweak mixing angle and $c_W^2 = 1 - s_W^2$. The new contributions are then parametrized by the $Z'Z^0$ mixing, $sin\theta_3$, and by the Z' mass, $M_{Z'}$. (The model fixes the new current $J_{Z'^0}$ and the mixing parameter γ, and then $sin\theta_3$.) The extra Z' is also exchanged in low energy processes. These global fits include neutral current, M_W and LEP data [20-23]. The unconstrained indirect limits in Table 1 correspond to 90% *c.l.* contours in the $M_{Z'} - sin\theta_3$ plane and are illustrative for they also depend on the top and Higgs masses, $m_{t,H}$, and on the strong coupling constant, α_s. The constrained indirect limits are the intersection of the unconstrained contours with Eq. (3). This Table makes apparent the model dependence of these bounds. In any case no piece of data requires an extra $U(1)$. This means that when the data are more precise all bounds on $M_{Z'}$ become more similar for they tend to a very large (decoupled) value. The constrained models are fitted with a definite

mixing angle ($sin\theta_3$) dependence on $M_{Z'}$, which is as emphasized above fixed by the model. In the unconstrained models $sin\theta_3$ is also a free parameter. LEP and atomic parity violating data imply typically $|sin\theta_3| \lesssim 0.01$. $HERA$ and eventually a large e^-e^+ collider will also provide new independent limits [10,11,24]. Astrophysical bounds on $M_{Z'}$ are $\sim 2-3\ TeV$ but rely on the existence of an almost massless fermion, called generically neutrino right-handed [25].

3. New Issues in Z' Physics

In this Section we revise recent work on extra gauge bosons [12–15].

3.1 Z' Mass Limit at LEP

LEP has taken data mainly at the Z peak, measuring M_Z and $\Gamma_Z, \Gamma_Z^{l,h}$, as well as several asymmetries and the τ polarization [1]. These high precision measurements provide indirect bounds on a new Z' [5–9]. As discussed in Section 2, these translate into strong constraints on the $Z'Z^0$ mixing angle but apparently not into an independent limit on $M_{Z'}$. However, LEP can provide such an independent (although eventually modest) limit [12]. There is one observable (and only one), the transverse-normal spin correlation in $\tau\bar{\tau}$ production, which fully and independently of its mixing measures the Z' mass at the Z peak. For a precision comparable to the standard model contribution $M_{Z'}$ can be bounded typically up to $\sim 130\ GeV$, which is a modest but independent bound. The $e^-(k_1) + e^+(k_2) \to \tau^-(p_1, s_1) + \tau^+(p_2, s_2)$ cross section $\frac{d\sigma}{d\Omega}(s_1^*, s_2^*)$, where $s_1^*(s_2^*)$ is the spin in the $\tau^-(\tau^+)$ rest frame, has only one contribution which is parity violating and T odd [26]. This gives the strongest constraint because we need a term knowing of the Z' for we want to bound $M_{Z'}$ and of the Z for it gives the dominant contribution at the Z peak. Moreover the term should be proportional to $\frac{M_Z^2}{M_{Z'}^2}$ (a real part) and to $\frac{M_Z}{\Gamma_Z}$ (an imaginary part), and then to an imaginary contribution. All this singles out the parity violating and T odd term of the differential cross section. It has the form

$$\frac{d\sigma}{d\Omega}(s_1^*, s_2^*) = ... + \frac{1}{16s}(s_{1y}^* s_{2x}^* + s_{1x}^* s_{2y}^*) G_2(s) sin^2\theta, \tag{4}$$

where s is the squared center of mass energy, the z axis is along the τ^- direction and θ is the center of mass $\tau^- e^-$ angle. In the presence of a new Z' (in obvious notation)

$$G_2(s) = G_2^{\gamma Z} + G_2^Z + G_2^{\gamma Z'} + G_2^{ZZ'} + G_2^{Z'} \simeq G_2^{\gamma Z} + G_2^Z + G_2^{ZZ'}. \tag{5}$$

G_2^Z vanishes at tree level but it is non zero at one loop and its size is similar to the tree level $G_2^{\gamma Z}$ and $G_2^{ZZ'}$ contributions [26]. A numerical analysis gives $M_{Z'}$

bounds ranging from M_Z to $2M_Z$ depending on the model and for the usual gauge coupling normalization. This is assuming an experimental precision similar to the standard model contribution to G_2. These bounds (although independent) are not competitive with present production limits except for extra interactions coupling only to leptons. In particular, for a new Z' coupling only to the electron minus the tau lepton number, $L_e - L_\tau$, LEP could give the best limit,

$$M_{Z'} < 133\frac{g'}{e}\ GeV, \tag{6}$$

where g' is the $Z_{e-\tau}$ gauge coupling and e the electric charge [17].

3.2 Diagnostics for Z' Gauge Couplings at Hadron Colliders

Large hadron colliders are the best place to look for a new gauge boson. As the standard Z was found at the $Sp\bar{p}S$ [27], a larger hadron collider will find or exclude a new Z' coupling to quarks and leptons with a mass $M_{Z'}$ up to near $5\ TeV$, assuming gauge couplings of the usual size [4]. If such extra interaction exists, large hadron colliders should also distinguish among different models. A new Z' of the E_6 type, for instance, should be uncovered observing an enhancement in the $e^-e^+(\mu^-\mu^+)$ invariant mass distribution near $M_{Z'}$. Then the forward-backward asymmetry will help to discriminate among different models [28]. Other decay channels could be eventually observed. The $Z' \to WW$ channel would measure the $Z'Z^0$ mixing angle. Other radiative decays $Z' \to f\bar{f}V,\ V = W, Z$ could serve as a diagnostic test for Z' gauge couplings [13]. These decays are proportional to $g^{f2}_{LZ}g^{f2}_{LZ'}$ and to $g^{f2}_{LZ}g^{f2}_{LZ'} + g^{f2}_{RZ}g^{f2}_{RZ'}$, respectively, where g stands for the corresponding gauge coupling. Thus, measuring both decays and different fermion channels the Z' couplings could be disentangled [29]. However these radiative decays can be very difficult to observe. Although for a large class of models and for $Z' \sim 1\ TeV$ some $f\bar{f}W$ and $f\bar{f}Z$ channels can have several hundreds of events, the large backgrounds probably reduce the interesting modes to a very few. The samples are relatively large to start with, due to the logarithmic singularity associated to the radiation by a fermionic line of an almost collinear W or Z. The possible signals are $l\bar{l}l\bar{l}, l\bar{l}\nu\bar{\nu}, l\bar{l}q\bar{q}, l\bar{\nu}q\bar{q}, \nu\bar{\nu}q\bar{q}$ and $q\bar{q}q\bar{q}$, where l stands for e and μ, ν for $\nu_{e,\mu,\tau}$ and q for any quark. The last two final states are unobservable due to the large backgrounds, mainly $q\bar{q}Z$ and $q\bar{q}q\bar{q}$, respectively. The $l\bar{l}q\bar{q}$ and $l\bar{\nu}q\bar{q}$ final states are populated and kinematically enhanced relative to the *a priori* large backgrounds $q\bar{q}Z$ and $q\bar{q}W$ for large and opposite transverse momenta of both leptons. $l\bar{l}l\bar{l}$ and $l\bar{l}\nu\bar{\nu}$ seem the most interesting signals. To build up the signals, however, the charged leptons must be identified in an event by event basis. This means that for $l\bar{l}l\bar{l}$ the different subsamples can have only several events. Then, although M_Z and $M_{Z'}$ can be reconstructed well, almost no statistics will be available. The $l\bar{l}\nu\bar{\nu}$ sample seems the most promising one. The number of events per year and per subsample (after cuts) can be several tenths, and comparing $e\bar{\mu}\nu\bar{\nu}$ with $e\bar{e}\nu\bar{\nu}(\mu\bar{\mu}\nu\bar{\nu})$ the $Z' \to l\bar{\nu}W$ and $l\bar{l}Z$ (and maybe $\nu\bar{\nu}Z$) couplings can be disentangled. At any rate a detailed numerical analysis with a proper generator and real cuts seems necessary to make definite predictions [30].

3.3 Radiative Corrections to ρ Due to a Strong Extra $U(1)$

At tree level and for a fixed electroweak mixing angle, an extra Z' mixing with the standard Z^0 lowers the Z mass predicted by the standard model [31]. Generically, indirect bounds on extra interactions have been obtained using tree level expressions for the new effects. As discussed in Section 2, there is no evidence of (piece of data requiring) a new Z'. This, together with the fact that the effect of a heavy top is also to lower M_Z, implies that a heavy top excludes a light Z' and viceversa. At one loop and depending of the relative size of the new contributions to the W and Z self-energies, the effect of a new Z' can be a relative increase of the Z mass. In Ref. [14] such a one loop calculation is presented for a strongly interacting extra $U(1)$. For a relatively large gauge coupling ($\sim 2\pi$) and for a relatively heavy Higgs ($\sim 800\ GeV$) and Z' ($\sim 8\ TeV$) the Z' contribution to the ρ parameter is negative. In such a case a top mass $\gtrsim 200\ GeV$ could be consistent with precise electroweak data. In specific models it is necessary, however, to check if other data pieces are consistent with a heavy top and a heavy but strongly interacting (and then effectively light) Z'.

3.4 Z' Limits Versus Fermion Mixing

Extra gauge interactions require new fermions if the theory has to be anomaly free [32]. We assume universality and that the extra $U(1)$ is not proportional to the standard model hypercharge. Hence any fit including new gauge interactions must also include extra fermions. Generically, all fits assume, often implicitly, that these fermions are relatively heavy and their mixing with the standard fermions zero. In this way they can be neglected because their oblique contributions are small [33]. At present, as emphasized before, no piece of data seems to require an extra Z'. Fits to fermion mixing with extra vector-like or exotic fermions alone have been also performed. In all cases data put bounds on this mixing ($\lesssim 0.1$) [15,34], except for the tau neutrino; in which case a non zero mixing with a sterile heavy neutrino is preferred (~ 0.2), although it is not compelling [35]. A global fit including with the extra gauge interactions the extra fermions would test the quality of previous fits.

4. Conclusions

Present *Tevatron* limits on $M_{Z'}$ vary from 300 to 400 GeV. The bounds on the mass of a new gauge boson are very model dependent, in particular those based on precise electroweak data ($M_{Z'} \lesssim 200 - 900\ GeV$). At present possible Z' effects are reduced to the size of experimental errors. *LEP* can bound the mass of an extra gauge boson couple to $L_e - L_\tau$ up to $\sim 130\ GeV$. If a new Z' below $\sim 5\ TeV$ exists, Z' physics if precise enough can be exciting at *LHC* and *SSC*. Radiative corrections as well as new fermions (matter) might be included in the fits to precise data and affect indirect limits on extra interactions.

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