1. Introduction

No signal of a new gauge boson has been observed up to now. Thus, although many extensions of the standard model require new gauge bosons, only limits on their interactions exist. We review present Z' bounds (Section 2), discuss future Z' constraints (Section 3) from TEVATRON, HERA and LEP, and give a brief review of the Z' diagnostics at future colliders (Section 4).

2. Present Z' Bounds

Grand unified theories (GUT’s) based, e.g., on the gauge group $SO(10)$ or $E_6$, as well as those based on superstring theory predict new gauge bosons. However, at present there are only (very model dependent) limits on their interactions. We review present constraints on new Z', presenting numerical results for the typical GUT, superstring-motivated, and left-right symmetric models: $\chi, \psi, \eta, LR$ (their definition is given for instance in Ref. 3). In Table 1 we collect the 95% C.L. direct bounds on $M_{Z'}$ from TEVATRON, corresponding to an integrated luminosity of $\sim 4 \, pb^{-1}$. Indirect bounds are given in columns two and three. These update the global fits of Ref. 5 by including the 1992 LEP data and other new results. (An update of the fits in Ref. 7 which use a larger data set yields similar results to those presented here.) The different data sets contributing to the total $\chi^2$ are gathered in Table 2. The unconstrained (constrained) bounds do not (do) assume a definite, minimal Higgs sector, and thus an unconstrained (constrained) $Z'Z^0$ mixing angle, $s_3$. In both cases the top and the Higgs masses and the strong coupling constant are free parameters.

|       | direct | indirect | indirect |
|-------|--------|----------|----------|
|       | (unconstrained) | (constrained) |       |
| $\chi$ | 320    | 380      | 670      |
| $\psi$ | 300    | 200      | 200      |
| $\eta$ | 310    | 210      | 440      |
| $LR$  | 350    | 430      | 990      |

* Invited talk presented by F. del Aguila at the Workshop on Physics and Experiments with Linear $e^+e^-$ Colliders, Hawaii, April 1993
Table 2. Data sets used to obtain the indirect $M_{Z'}$ limits. Neutral-current parameters, $\nu q, \nu_{\mu} e, e H$, and gauge boson masses are summarized in Ref. 2. LEP data were presented at the XXVIIIth Rencontre de Moriond 6.

| Quantity | Experimental Value | Correlation Matrix |
|----------|-------------------|--------------------|
| $\nu q$  | $g_L^q$ 0.3003 ± 0.0039 | 1. |
|         | $g_R^q$ 0.0323 ± 0.0033 | 1. |
|         | $\theta_L$ 2.49 ± 0.037 | 1. |
|         | $\theta_R$ 4.69 ± 0.38 | 1. |
| $\nu_{\mu} e$ | $g_A^\nu_{\mu}$ $-0.508 ± 0.015$ | 1. $-0.04$ |
|         | $g_C^\nu_{\mu}$ $-0.035 ± 0.017$ | $-0.995$ $-0.79$ |
| $e H$    | $C_{1u}$ $-0.214 ± 0.046$ | 1. $-0.995$ $-0.79$ |
|         | $C_{1d}$ $0.359 ± 0.041$ | $-0.995$ 1. 0.79 |
|         | $C_{2u} - \frac{1}{2} C_{2d}$ $-0.04 ± 0.13$ | $-0.79$ 0.79 1. |
| $p \bar{p}$ | $M_W$ 79.91 ± 0.39 GeV | 1. $-0.154$ 0.023 0.012 0.070 |
|         | $M_W/M_Z$ 0.8813 ± 0.0041 | 1. |

LEP

| $M_Z$ | 91.187 ± 0.007 GeV | 1. $-0.154$ 0.023 0.012 0.070 |
| $\Gamma_Z$ | 2488 ± 7 MeV | $-0.154$ 1. $-0.143$ 0.007 0.005 |
| $g^\phi_1$ | 41.446 ± 0.169 nb | 0.023 $-0.143$ 1. 0.126 0.003 |
| $R_l$ | 20.833 ± 0.056 | 0.012 0.007 0.126 1. 0.008 |
| $A_{FB}$ | 0.016 ± 0.002 | 0.070 0.005 0.003 0.008 1. |

Indirect $M_{Z'}$ limits have a large, model dependent correlation with the other variables in the fit. However, the value of the weak angle and upper limits on the top quark mass are insensitive to large variations of the $M_{Z'}$ values. In general LEP data put stringent limits on the $Z'Z^0$ mixing angle 5,7,8.

Many extensions of the standard model, like the ones considered here, predict the existence of new fermions. The $Z'$ limits, however, change little when fermion mixing between standard and new (vector-like) fermions is allowed 9.

Stringent limits on new interactions can also be derived from astrophysical constraints. The corresponding limits on the $Z'$ mass are of the order of $2 - 3 \, \text{TeV}^{10}$, but they rely on the existence of an almost massless right-handed neutrino and can be avoided. Baryogenesis may eventually also pose a problem for extended gauge theories with heavy neutrinos and new gauge bosons in the $\text{TeV}$ range 11.

3. Future $Z'$ Constraints

In Table 3 we present the estimates for the forthcoming bounds on $M_{Z'}$. The limits for TEVATRON correspond to an integrated luminosity, already accumulated, $\int \mathcal{L} dt = 25 (100) \, \text{pb}^{-1}$; whereas the bounds at HERA assume polarized beams and an integrated luminosity $\int \mathcal{L} dt = 100 \, \text{pb}^{-1}$.

3.1. TEVATRON

The direct bounds on $M_{Z'}$ are robust 7,12. They do not depend on the $Z'Z^0$ mixing angle and are somewhat insensitive to the top and Higgs masses.
Table 3. Future constraints on the mass of new gauge bosons (in GeV). The blank in the 95\% C.L. HERA bounds indicates no sensitivity to $Z'$ masses above the $Z$ mass.

|        | TEVATRON $\int L\, dt = 25\, \text{(100) pb}^{-1}$ | HERA |
|--------|-------------------------------------------------|------|
| $\chi$ | 470 (620)                                       | 240  |
| $\psi$ | 450 (600)                                       | –    |
| $\eta$ | 460 (610)                                       | 180  |
| $LR$   | 510 (660)                                       | 370  |

3.2. HERA

The sensitivity of HERA to the exchange of a heavy neutral $Z'$ boson and its discovery potential has been systematically analysed in Ref. 13. The corresponding limits on new gauge interactions are not competitive, for instance, with those from TEVATRON (see Table 3). The diagrams involved are the same in both cases but new gauge bosons are produced in the $s$-channel at hadron colliders and exchanged in the $t$-channel at lepton-hadron colliders. In contrast with TEVATRON, HERA is sensitive to the relative sign of $Z'$ couplings. Due to the different weight of gauge couplings, HERA also enhances its relative potential for definite choices of gauge couplings. At any rate the limits expected at TEVATRON rule out the possibility of observing a $Z'$ at HERA first.

3.3. LEP

A similar fit to the one in Table 1 but with improved LEP errors makes even more apparent the comments in the previous Section. For the unconstrained case a global fit to precise standard model data gives only a weak $Z'$ mass limit.

4. $Z'$ Diagnostics at Future Colliders

Large colliders can probe new gauge interactions for $Z'$ masses up to several $\text{TeV}$. If the samples are large enough the determination of $Z'$ gauge couplings to matter can be attempted. The hadron and lepton colliders are discussed separately below for the case of one extra neutral gauge boson coupled minimally. (Large colliders will also allow for measuring non-minimal coefficients of a general parametrization with effective operators (see for instance Ref. 14).)

4.1. LHC/SSC

A detailed discussion is presented by M. Cvetič in this Workshop. $Z'$ physics is described by eight parameters: the $Z'$ mass and width, $M_{Z'}$, $\Gamma_{Z'}$, five gauge couplings, $g_{Z'}$, $\gamma_L^l = \frac{(g_{uL}^Z)^2}{(g_{uL}^Z)^2 + (g_{uR}^Z)^2}$, $\gamma_L^q = \frac{(g_{qL}^Z)^2}{(g_{qL}^Z)^2 + (g_{qR}^Z)^2}$, $U = \frac{(2g_{qL}^Z)^2}{g_{uL}^Z}$, $D = \frac{(2g_{uR}^Z)^2}{g_{qL}^Z}$ (no sensitivity is expected at LHC/SSC to the sign of the $Z'$ gauge couplings to quarks and leptons), and the $Z'Z^0$ mixing angle, $s_3$. The cross section for $pp \to Z' \to t\bar{t}$ determines the $Z'$ mass, width, and gauge coupling. Combining the ratio of this cross section in two rapidity bins with the forward-backward asymmetry, the rare decay modes $Z' \to Wl\bar{l}$, and three associated productions $pp \to Z'V (V = Z, W, \gamma)$, and assuming inter-family universality, small $Z'Z^0$ mixing, and the $Z'$ charge commuting with the $SU(2)_L$ generators, three out of four normalized couplings could be extracted. $\gamma_L^q$ requires the measurement of the $pp \to Z' \to q\bar{q}$ cross section. This is a difficult task; however, it has been recently claimed that it may be possible.
Finally, with appropriate cuts, $s_3$ may be measured by studying the rare $Z'$ decays into two charged leptons plus two neutrinos $^{17}$. Hence, except for the signs of the gauge couplings to quarks and leptons, all parameters fixing the interactions of a new neutral gauge boson with a mass $\sim 1-2 \, \text{TeV}$ may be determined at large hadron colliders.

4.2. $e^+e^-$

LEP 200 will measure $M_{W'}$ with high precision, improving the top mass and eventually the Higgs mass limits and the indirect $M_{Z'}$ lower bounds. Larger $e^+e^-$ colliders may produce a new $Z'$ on-shell, but a more realistic scenario may be the production of a new heavy gauge boson far off-shell. (A detailed discussion of this case can be found in Ref. 18 (see also Ref. 19).) In both cases the $e^+e^- \rightarrow Z' \rightarrow W^+W^-$ channel offers the possibility of measuring the $Z'Z^0$ mixing angle, $s_3^{20}$. However, the $s_3$ bounds seem to exclude this possibility for an $e^+e^-$ collider with a center of mass energy of 500 GeV (NLC). On the other hand, it is claimed that the $e^+e^- \rightarrow Z' \rightarrow f\bar{f}$ channel distinguishes between extended gauge models for $Z'$ masses up to 3 TeV at NLC $^{18}$. This requires taking into account radiative corrections and a good control of the experimental set up. Similarly to the LHC/SSC case one can determine (some of) the parameters describing the $Z'$ interactions. For a $Z'$ much heavier than 500 GeV ($\sim 1$ TeV) no determination of the $Z'$ width and mass seem to be possible, since the $Z'$ amplitudes are proportional to $\frac{g_{Z'}^2}{M_{Z'}}$. However, with final state quark identification $\sigma^l$, $R = \frac{a^h}{a^l}$, and $A_{L,B}^{l,h}$ will allow one to measure not only $\frac{g_{Z'}^2}{M_{Z'}}$ and $\gamma^q_L, \gamma^l_L, \tilde{U}, \tilde{D}$, but will also provide a unique determination of the relative signs of the hadronic and leptonic couplings $^{21}$.

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6. References

1. See for example, J.L. Hewett in these Proceedings; J.L. Hewett and T.G. Rizzo, Phys. Rep. 183 (1989) 193.
2. Review of Particle Properties, Phys. Rev. D45 (1992) III-59; P. Langacker, in Precision Tests of the Standard Electroweak Model (World Scientific, Singapore, 1993).
3. F. del Aguila, M. Cvetič and P. Langacker, Phys. Rev. D48 (1993) R969.
4. F. Abe et al., CDF Collaboration, Phys. Rev. Lett. 67 (1991) 2418.
5. F. del Aguila, W. Hollik, J. Moreno and M. Quirós, Nucl. Phys. B372 (1992) 3.
6. V. Innocente, in XXVIIIth Rencontre de Moriond, Electroweak Interactions and Unified Theories, Les Arcs, 1993.
7. P. Langacker and M. Luo, Phys. Rev. D45 (1992) 278. Future possibilities are discussed in P. Langacker, A. K. Mann, and M. Luo, Rev. Mod. Phys. 64 (1992) 87.
8. G. Altarelli et al., Nucl. Phys. B342 (1990) 15; Phys. Lett. B261 (1991) 146;
B263 (1991) 459; M.C. González García and J.W.F. Valle, Phys. Lett. B259 (1991) 365; T.G. Rizzo, MAD/PH/626, 1990; J. Layssac, F.M. Renard and C. Verzegnassi, Z. Phys. C53 (1992) 97.

9. E. Nardi in these Proceedings; P. Langacker and D. London, Phys. Rev. D38 (1988) 886; E. Nardi, E. Roulet and D. Tommasini, Nucl. Phys. B386 (1992) 239; E. Nardi, UM-TH 92-19, 1992; J. Bernabéu, E. Nardi and D. Tommasini, UM-TH 93-8, 1993.

10. J.W.F. Valle, in XIII Warsaw Symposium on Elementary Particle Physics, ed. Z. Ajduk, S. Pokorski and A. Wróblewski (Kazimierz, 1990).

11. W. Buchmüller and T. Yanagida, DESY 92-172, 1992.

12. F. del Aguila, J.M. Moreno and M. Quirós, Phys. Rev. D40 (1989) 2481; D41 (1990) 134; (E) D42 (1990) 262.

13. H.-U. Martyn et al., in Physics at HERA, ed. W. Buchmüller and G. Ingelman (DESY, Hamburg, 1992), p. 987; see also P. Haberl et al., ibid, p. 980; F. Cornet and R. Rückl, Phys. Lett. B184 (1987) 263; in HERA Workshop, ed. R.D. Peccei (DESY, Hamburg, 1987), p. 771; J. Blümlein et al., ibid, p. 687.

14. J.-M. Frère, J.M. Moreno, M. Tytgat and J. Orloff, Phys. Lett. B292 (1992) 348.

15. M. Cvetič and P. Langacker, Phys. Rev. D46 (1992) R14; Phys. Rev. D46 (1992) 4943; M. Cvetič, B. Kayser and P. Langacker, Phys. Rev. Lett. 68 (1992) 2871; T.G. Rizzo, Phys. Lett. B192 (1987) 125; J.L. Hewett and T.G. Rizzo, ANL-HEP-PR-92-33, 1992.

16. P.K. Mohapatra in these Proceedings; P.K. Mohapatra, Mod. Phys. Lett. A8 (1993) 771; T.G. Rizzo, ANL-HEP-PR-93-18, and references therein.

17. F. del Aguila, B. Allés, Ll. Ametller and A. Grau, Phys. Rev. D48 (1993) 425.

18. A. Djouadi, A. Leike, T. Riemann, D. Schaile and C. Verzegnassi, Z. Phys. C56 (1992) 289.

19. J.L. Hewett and T.G. Rizzo, ANL-HEP-CP-91-90, 1991; T.G. Rizzo, ANL-HEP-CP-91-96, 1991.

20. N. Paver in these Proceedings; P. Comas and A. Méndez, Phys. Lett. B260 (1991) 211; A.A. Pankov and N. Paver, IC/92/273, 1992.

21. F. del Aguila, M. Cvetič and P. Langacker, in preparation.