DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 86-167
December 1986

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ISSN 0418-9833

NOTKESTRASSE 85 · 2 HAMBURG 52

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* Invited Talk at the VIth International Conference on Proton-Antiproton Physics, Aachen, 1986.

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ABSTRACT

Focussing on a superstring inspired model with one extra U(1) symmetry at low energies I illustrate the prospects of detecting new gauge bosons at future ($\bar{p}$)p, e^+e^- and ep colliders.

The search for physics beyond the standard model of strong and electroweak interactions of quarks and leptons is one of the main tasks of future high energy machines. In the absence of a clear and completely trustworthy guidance by theory, it appears very useful to study the phenomenology of a large variety of possible new particles and interactions. In this talk, I shall consider new gauge bosons and illustrate the prospects of detecting them at ($\bar{p}$)p, e^+e^- and ep colliders. Theoretically, the existence of new gauge bosons associated with extensions of the standard $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge structure is suggested, for example, by left-right symmetric, grand-unified and superstring models[1-3]. For definiteness and brevity, I will concentrate on the simple scenario of a $SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ electroweak gauge symmetry at low energies where the extra U(1) group originates from an E_6 grand-unified theory broken at very high scales.

Extra U(1) models have recently gained considerable interest as low energy limits of superstring theories[4]. Roughly speaking, compactification of the heterotic $E_8 \times E_8'$ superstring in 10 dimensions on suitable Calabi-Yau manifolds may yield a supersymmetric E_6 grand-unified theory in 4 dimensions with the E_6 symmetry broken by the Wilson loop mechanism to some subgroup of E_6 at the Planck scale[3-6]. In particular, E_6 may directly break down to $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$. Although the appearance of one extra U(1) in the low-energy limit is by no means a theorem, it certainly represents an interesting case for phenomenological studies.

The model introduced above contains three neutral bosons, the γ and standard Z associated with $SU(2)_L \times U(1)_Y$ and a new boson Z' associated with $U(1)_{Y'}$. Furthermore, the 15 helicity components of a standard fermion family form, together with new fermion species, a fundamental 27-plet of E_6. The fields and quantum numbers of the lightest family are specified in Table 1. Corresponding assignments are assumed for the heavier families. The fermionic currents coupled to γ, Z and Z', respectively, are given by

$$J^{\mu}_{em} = \sum_f \bar{f}\gamma^{\mu} Q_f f \tag{1a}$$

$$J^{\mu}_{NC} = \sum_f \left[\bar{f}_L\gamma^{\mu}(T^L_{3f} - \sin^2\theta_W Q_f) f_L + \bar{f}_R\gamma^{\mu}(-\sin^2\theta_W Q_f) f_R\right] \tag{1b}$$

$$J'^{\mu} = \sum_f \left[\bar{f}_L\gamma^{\mu} Y'^L_f f_L + \bar{f}_R\gamma^{\mu} Y'^R_f f_R\right] \tag{1c}$$

Table 1: Quantum numbers of the left-handed fields of a fermion 27-plet of E_6.

E_6	SO(10)	SU(5)	$SU(3)_c$	$SU(2)_L$	Y	L-fields	$Y'\cdot\sqrt{15}$
27	16	10	3	2	1/6	u d	1
			$\bar{3}$	1	-2/3	u^c	
			1	1	1	e^c	
		$\bar{5}$	$\bar{3}$	1	1/3	d^c	-1/2
			1	2	-1/2	ν_e e	
		1	1	1	0	N^c_e	5/2
	10	5	3	1	-1/3	h	-2
			1	2	1/2	E^c N^c_E	
		$\bar{5}$	$\bar{3}$	1	1/3	h^c	-1/2
			1	2	-1/2	ν_E E	
	1	1	1	1	0	n	5/2

where $f_{L,R} = \frac{1}{2}(1\mp\gamma_5)f$. The electromagnetic charges $Q_f = T^L_{3f} + Y_f$, the third components of the weak isospin T^L_{3f} and the new $U(1)_{Y'}$ charges $Y'^L_f = Y'_f$, $Y'^R_f = -Y'_{fc}$ can be inferred from Table 1. The Weinberg angle θ_W is defined as usual in terms of the $SU(2)_L$ and $U(1)_Y$ gauge couplings, g and g_Y:

$$\sin^2\theta_W = \frac{g_Y^2}{g^2 + g_Y^2} . \tag{2}$$

The Higgs bosons also belong to a 27-plet of E_6 and, hence, one only has $SU(2)_L$ doublets and singlets. Some of them acquire nonvanishing vacuum expectation values such that $SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ is broken spontaneously to $U(1)_{em}$. In general, Z and Z' are not the physical fields which become massive after spontaneous symmetry breaking. The mass eigenstates Z_1 and Z_2 are rather mixtures of Z and Z',

$$\begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} Z \\ Z' \end{pmatrix} \tag{3}$$

where, without further assumptions on the Higgs sector, the mixing angle θ can take any value in the range $-\pi/2 \leq \theta \leq \pi/2$. Evidently, the state Z_1 with the lower mass eigenvalue m_{Z_1} is to be identified with the already observed neutral weak boson. Therefore, the main focus is on the heavier state Z_2 with mass m_{Z_2}. In the absence of mixing, m_{Z_1} coincides with the mass m_Z of the standard Z boson as can be seen from the relation

$$m_Z^2 = \cos^2\theta\, m^2_{Z_1} + \sin^2\theta\, m^2_{Z_2} \tag{4}$$

implied by eq.(3). With the above specifications it is straightforward to write down the effective neutral current Lagrangian of this model:

$$\mathcal{L} = e J^{\mu}_{em} A_{\mu} + \frac{g}{\cos\theta_W}\left(J^{\mu}_1 Z_{1\mu} + J^{\mu}_2 Z_{2\mu}\right) \tag{5}$$

with

$$\begin{pmatrix} J_1 \\ J_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} J_{NC} \\ \frac{g_{Y'}}{g}\cos\theta_W J' \end{pmatrix} \qquad (6)$$

and J^{μ}_{em}, J^{μ}_{NC} and J'^{μ} as given in eq.(1). Furthermore, the $U(1)_{Y'}$ gauge coupling $g_{Y'}$ takes the value

$$g_{Y'} = \sqrt{\frac{5}{3}}\ \frac{e}{\cos\theta_W} \qquad (7)$$

corresponding to the assumption that $g_{Y'}$ evolves in the same way as the $U(1)_Y$ coupling g_Y. The normalization of $g_{Y'}$ and the charges Y' is such that in the E_6 symmetry limit (when $\sin^2\theta_W = 3/8$) $g_{Y'}$ is equal to the $SU(2)_L$ coupling $g = e/\sin\theta_W$. As a side remark, all superpartners are considered very heavy and, hence, are disregarded.

The neutral current sector of the model defined by the Lagrangian eq.(5) involves four parameters: the boson masses m_{Z_1} and m_{Z_2}, the Weinberg angle θ_W and the Z-Z' mixing angle θ. If the Higgs fields responsible for electroweak symmetry breaking are all $SU(2)_L$ doublets and singlets as it is the case in the superstring scenario, one has the additional relation

$$\rho = \frac{m_W^2}{m_Z^2\cos^2\theta_W} = 1 \qquad (8)$$

with m_Z^2 given by eq.(4). Then, only three of the above parameters are independent. Considering m_{Z_1} as fixed by experiment and m_{Z_2} and θ as essentially free parameters, one can compute the Weinberg angle from

$$\sin^2\theta_W = \frac{1}{2}\left(1 - \sqrt{1 - 4\mu^2/m_Z^2}\right) \qquad (9)$$

and eq.(4) as a function of m_{Z_2} and θ. Here, μ = 38.65 GeV includes the standard electroweak corrections[7], while small corrections due to the Z'-boson and new E_6 fermions (and superpartners) are neglected. Of course, the mixing induced shift of $\sin^2\theta_W$ from the standard model

value is restricted by experiment. These constraints can directly be turned into bounds[6] on m_{Z_2} and θ as shown later.

Evidence for the presence of a second neutral boson can arise from production of Z_2 and subsequent decay into ordinary fermions and, possibly new particles, from virtual Z_2 exchange and from modifications of the standard neutral current interactions due to Z-Z' mixing. In more detail, because of mixing the couplings of the lower mass eigenstate Z_1 to the ordinary fermions deviate from the standard NC couplings as obvious from the inequality

$$J_1 \neq J_{NC} \qquad (10)$$

and detailed in eq.(6). Furthermore, according to eq.(4) m_{Z_1} differs from the standard model value m_Z in that

$$m_{Z_1} = \sqrt{m_Z^2/\cos^2\theta - m_{Z_2}^2\tan^2\theta} \leq m_Z \qquad (11)$$

and, consequently, the Weinberg angle $\bar{\theta}_W$ obtained from the W and Z_1 mass ratio is different from the angle θ_W defined by eqs.(8) and (9):

$$\sin^2\bar{\theta}_W = 1 - \frac{m_W^2}{m_{Z_1}^2} \leq 1 - \frac{m_W^2}{m_Z^2} = \sin^2\theta_W \ . \qquad (12)$$

Needless to say, in contrast to a Z_2 resonance peak the mixing effects provide rather ambiguous evidence in the sense that they can be easily confused with other new physics such as compositeness which may induce similar small deviations from the standard model. However, it is also true that strong constraints on Z_2 can be obtained if no effect is seen.

The present bounds on m_{Z_2} and θ are exemplified in Figs. 1 and 2. In deriving the constraints indicated in Fig. 1 all relevant low-energy neutral current data[8] as well as the W and Z mass measurements[9] by UA1 and UA2 have been used. On the other hand, the bounds exhibited

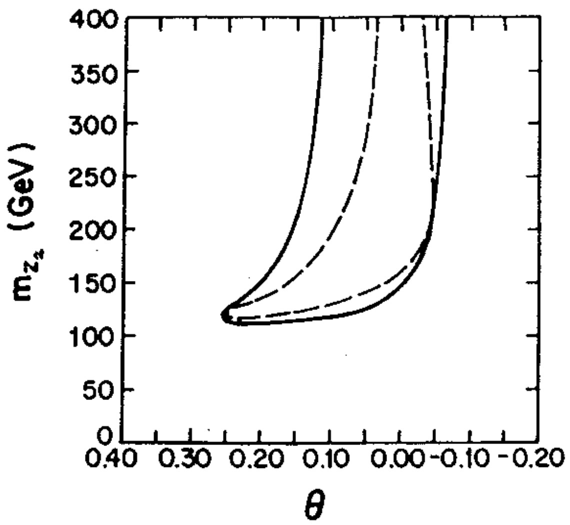

Fig.1 Values of the mass and mixing angle of the E_6 boson Z_2 defined in the text which are excluded at 90% c.l. by present-day neutral current data and W and Z mass measurements (reproduced from ref. 2 with $\theta \to -\theta$). The full (dashed) curve shows the boundary obtained without (with) the Higgs constraint eq.(8).

in Fig. 2 follow from the negative result of the UA1 and UA2 searches[9] for a second Z' resonance decaying into e^+e^- in $\bar{p}p$ collisions at $\sqrt{s}$ = 630 GeV. The theoretical curves in Fig. 2 result from two extreme assumptions on the masses of the new fermion species in the three E_6 multiplets which replace the three standard families (m_t = 40 GeV):

$$\begin{aligned} &(A) \quad m_{f_{new}} > m_{Z_2}/2 \\ &(B) \quad m_{f_{new}} \lesssim 30 \text{ GeV} \quad . \end{aligned} \tag{13}$$

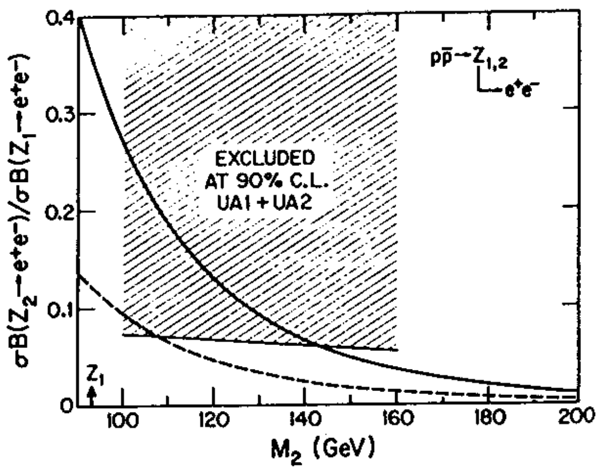

Fig.2 Lower limits on the mass of the same E_6 gauge boson as in Fig.1 following from the absence of Z_2 resonance production and decay in $\bar{p}p$ collisions at $\sqrt{s}$ = 630 GeV (taken from ref.10). The solid (dashed) curve refers to assumption (A) (assumption (B)) on the exotic fermion masses stated in eq.(13).

For the corresponding ratios of the e^+e^- branching fractions of Z_1 and Z_2 one finds

$$\frac{B(Z_2 \to e^+e^-)}{B(Z_1 \to e^+e^-)} \simeq \begin{cases} 1.3 & (A) \\ 0.45 & (B) \end{cases} \quad . \tag{14}$$

As can be seen from Figs. 1 and 2, present experimental knowledge permits the existence of the Z_2 boson with a mass as light as 120 - 140 GeV and rather small Z-Z' mixing. Similar bounds are obtained in ref.6 and 11.

Now I shall discuss possible signals from Z_2 at future colliders and present some rough estimates of detection limits. Effects of Z_2 in e^+e^- collisions at LEP and SLC have been studied in ref.11 including shifts in the lighter Z mass m_{Z_1} and in $\sin^2\theta_W$, alterations to the total e^+e^- cross sections and modifications of the forward-backward asymmetries. A few clarifying remarks on this analysis are necessary. In ref.11 (Angelopoulos et al.) spontaneous symmetry breaking is assumed to be due to two Higgs doublets (with $Y = \pm\frac{1}{2}$) and one Higgs singlet field acquiring the vacuum expectation values v, $\bar{v}$ and x, respectively. In terms of the latter, the boson masses m_{Z_1} and m_{Z_2} and the mixing angle θ are given by[11]

$$m_{Z_1,Z_2} = m_Z\sqrt{\frac{1}{2}\left(1+b\mp\sqrt{(1-b)^2+4a^2}\right)} \qquad (15a)$$

$$\tan 2\theta = 2a/(b-1) \qquad (15b)$$

where

$$a = \frac{1}{3}\sin\theta_W \frac{4v^2-\bar{v}^2}{v^2+\bar{v}^2} \qquad (16a)$$

$$b = \frac{1}{9}\sin^2\theta_W \frac{25x^2+16v^2+\bar{v}^2}{v^2+\bar{v}^2} \qquad (16b)$$

and

$$m_Z = \sqrt{\frac{1}{2}(g^2+g_Y^2)(v^2+\bar{v}^2)} \quad . \qquad (17)$$

While the mass of the lighter boson Z_1 is kept fixed at the nominal standard model value m_{Z_1} = 93.3 GeV, the mass of Z_2 varies with x/v and $\bar{v}$/v as indicated in Fig. 3. The region of the $\left(\frac{\bar{v}}{v}, \frac{x}{v}\right)$-plane considered in this study is suggested by a particular no-scale model[6]. Furthermore, it can be easily seen from eqs.(15b) and (16) that the mixing angle θ decreases when $\frac{x}{v}$ increases. For example, θ ≈ (20-30)° for x/v ≈ 2 and θ ≈ 0.5° for x/v ≈ 10. Also shown in Fig. 3 are contours of fixed values of the difference $\Delta = \sin^2\theta_W - \sin^2\bar{\theta}_W$, the two weak angles

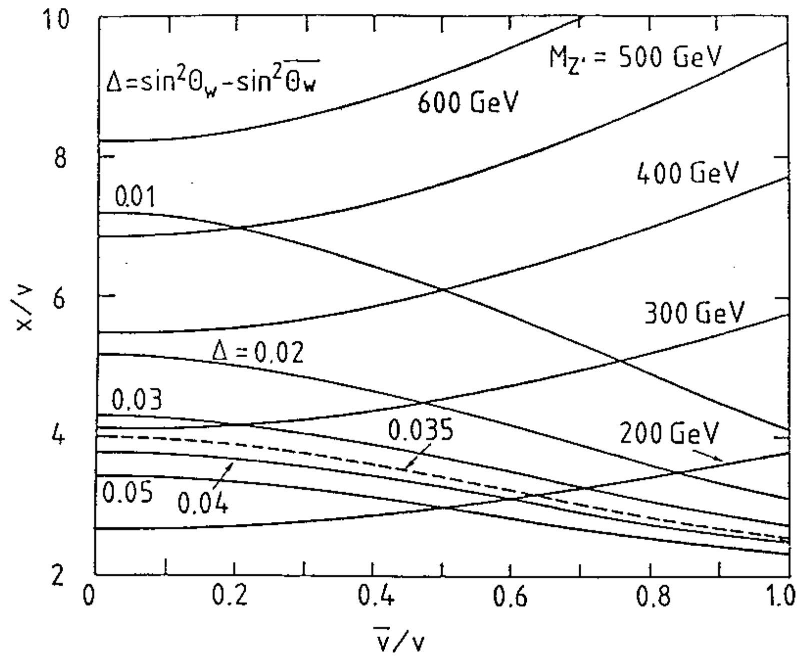

Fig.3 Contours of given values of m_{Z_2} and $\Delta = \sin^2\theta_W - \sin^2\bar{\theta}_W$ in the $\left(\frac{\bar{v}}{v}, \frac{x}{v}\right)$-plane (taken from ref.11). The mass of the lighter boson Z_1 is fixed at m_{Z_1} = 93.3 GeV. The dashed line indicates the present 1σ bound Δ < 0.035.

being defined in eq.(12). The dashed curve denotes the present-day 1σ-limit Δ < 0.035 which for $\bar{v} \approx v(\bar{v} \approx 0)$ excludes the existence of Z_2 with $m_{Z_2} \lesssim$ 150(300) GeV and θ ≳ 10°(4°). Undoubtedly, considerably larger masses and smaller mixing angles will be probed at LEP and SLC where Δ can be determined much more accurately. This is particularly true once not only m_{Z_1} (LEP I/SLC) but also m_W (LEP II) is known very precisely. Another possibility is to search for effects from Z_2 on the $e^+e^- \to \bar{f}f$ cross sections σ_f and forward-backward asymmetries

$$A_f = \left[\sigma_f\left(0 \le \delta \le \frac{\pi}{2}\right) - \sigma_f\left(\frac{\pi}{2} \le \delta \le \pi\right)\right] / \sigma_f \qquad (18)$$

where δ is the angle between the incoming e^- and the outgoing fermion f. Fig. 4 illustrates the modifications to A_μ at the Z_1 peak, i.e. at $\sqrt{s} = m_{Z_1}$, and at the LEP II c.m. energy $\sqrt{s}$ = 180 GeV. The prospects of detecting such off-shell Z_2 signals at the Z_1 peak look quite promising. On the one hand, the present-day limits still permit sizeable effects, on the other hand, A_μ is expected to be measured very accurately at LEP I[12]. At least the statistical error will only amount to $\delta A_\mu \approx \pm$ few ‰. As shown in Fig. 4, with a precision $\delta A < 0.01$ one will either observe a deviation from the standard model asymmetry or rule out the existence of Z_2 in the whole parameter space studied in Fig 3. It also becomes obvious from Fig. 4 that asymmetry measurements at LEP II are not very useful in testing this particular Z_2 model, but they may do better for other models[11]. Finally, I should point out that the signals exhibited in Figs. 3 and 4 are mainly induced by Z-Z' mixing. Therefore, they are not very sensitive to the specific couplings of the Z_2 and, as remarked earlier, cannot provide unambiguous evidence for the existence of Z_2. Unmistakeable evidence would only come from resonance production of Z_2, i.e. $e^+e^- \to Z_2 \to f\bar{f}$ with $2m_f < m_{Z_2} < \sqrt{s}$. Given the present bounds (Figs. 1 and 2), it is not excluded but extremely unlikely that the c.m. energies reachable at LEP II will be sufficient. This calls for an e^+e^- collider exploring the energy range beyond LEP II.

In ep collisions, a second neutral boson would contribute to neutral current $\overset{(-)}{e}q \to \overset{(-)}{e}q$ scattering via exchange in the t-channel. The possible existence of a relatively light Z_2 makes the case interesting for HERA[11,13] where at the design energy $\sqrt{s}$ = 314 GeV electroweak physics can be investigated at momentum transfers $Q^2 = -t > 10^4$ GeV^2 [14,15]. However, it turns out that the effects of Z_2 on the NC cross sections are rather marginal. Even for m_{Z_2} as low as 100 GeV and at the highest Q^2 accessible at HERA with reasonable statistics, the cross sections do not change by more than a few percent. This is mainly for two reasons: firstly, the Z_2 couplings to the ordinary fermions are relatively weak as compared to the Z_1 couplings and, secondly, the

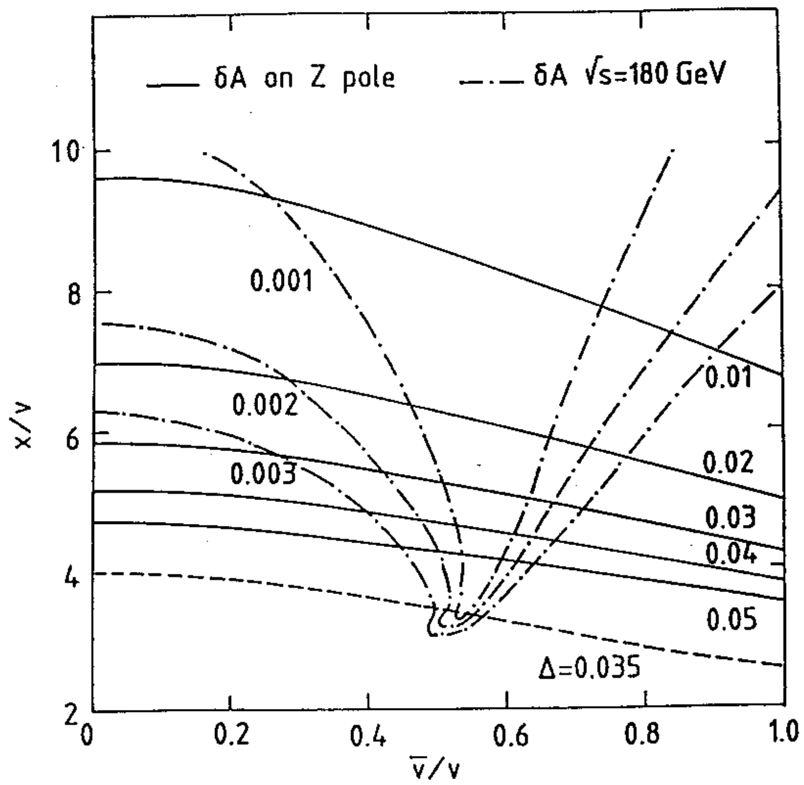

Fig.4 Contours indicating the changes δA in the forward-backward asymmetry A_μ due to the presence of Z_2 for the same region of Higgs parameters as in Fig.3 (taken from ref.11). The mass of the observed boson, $\bar{Z}$ in the standard model and Z_1 in the two Z model, is taken to be 93.3 GeV. Considered are the LEP I energy $\sqrt{s} = m_Z = m_{Z_1}$ and the representative LEP II energy $\sqrt{s}$ = 180 GeV. The dashed curve represents the bound $\Delta < 0.035$ as in Fig.3.

interferences between the Z_2 amplitude and the γ and Z_1 amplitudes cancel partly as a result of the particular signs of the relevant Y' charges given in Table 1. Hence, one must study more sensitive quantities in order to probe the existence of Z_2 beyond the present limits. Similarly as in other searches for new physics in ep collisions[15], the most sensitive experiments are asymmetry measurements using longitudinally polarized $e^{\pm}$ - beams. At HERA, such beams are under design[16]. In terms of the inclusive differential cross sections $d\sigma(e_h^s p) \equiv d\sigma(e_h^s p \to e^s X)/dx dQ^2$, x being the fraction of the proton momentum carried by the interacting (anti)quark, the asymmetries are defined by

$$A_{hh'}^{ss'} = \frac{d\sigma(e_h^s p) - d\sigma(e_{h'}^{s'} p)}{d\sigma(e_h^s p) + d\sigma(e_{h'}^{s'} p)} \quad . \qquad (19)$$

In the above, the upper indices s and s' denote the lepton charges, $s(s') = \pm$ for $e^{\pm}$, while the lower indices h and h' specify the lepton polarizations, h(h') = L,R for left-handed and right-handed states, respectively. Making the same assumptions on the Higgs sector as quoted in the last paragraph and restricting themselves to the parameter space considered in Figs. 3 and 4, Angelopoulos et al.[11] have studied the effects from Z_2 on some of the asymmetries at HERA. F. Cornet and I[13] have extended the analysis to a considerably wider range of the Z_2 parameters using only the Higgs constraint eq.(8), and to all possible asymmetries. This enabled us to identify those asymmetries which are most sensitive to the presence of Z_2 and to directly compare the existing bounds on m_{Z_2} and θ with the values probed at HERA for a given experimental precision. An illustration of our results is presented in Fig. 5. This figure shows contours in the (θ, m_{Z_2})-plane corresponding to

$$\delta A = |A(\gamma, Z) - A(\gamma, Z_1, Z_2)| = 0.04 \qquad (20)$$

where $A(\gamma, Z)$ and $A(\gamma, Z_1, Z_2)$ denote the predictions of the standard and the two Z-model, respectively, on a particular asymmetry $A = A_{hh'}^{ss'}$. For comparison with the present constraints on Z_2 also exhibited in

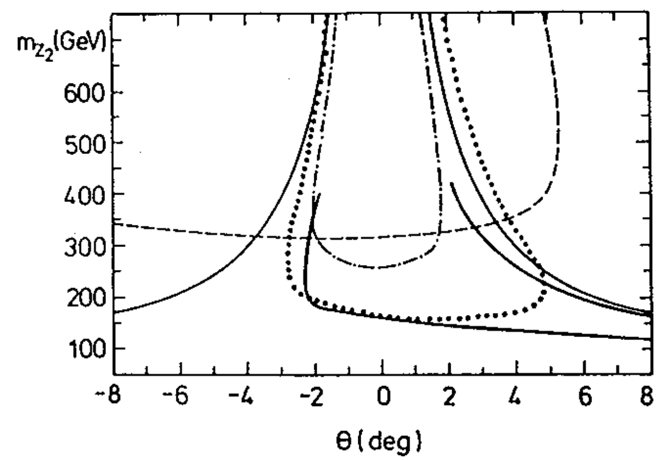

Fig.5 Regions in m_{Z_1} and θ which could be probed in ep collisions at HERA ($\sqrt{s}$ = 314 GeV) by measuring the asymmetries A_{RL}^{-+} (dashed), A_{LR}^{--} (dashed-dotted) and A_{RR}^{-+} (dotted) for x = 0.3 and $Q^2 = 2\cdot10^4$ GeV^2 with a precision $\delta A = 0.04$ (taken from ref.13). The other curves exhibit present-day constraints. Values of m_{Z_2} and θ inside the boundary drawn as thick full curves are compatible with neutral current phenomenology (dashed curve in Fig.1). Values outside the thin full curves are excluded by the W and Z mass measurements which imply $\Delta = \sin^2\theta_W - \sin^2\bar{\theta}_W < 0.035$ (corresponding to the dashed curves in Figs.3 and 4).

Fig. 5, the more sensitive ones of the polarization (s=s'), charge (h=h') and mixed (s≠s', h≠h') asymmetries have been selected. As a somewhat extreme but not inconceivable kinematical point we have chosen x = 0.3 and $Q^2 = 2\cdot10^4$ GeV^2. For these values of x and Q^2, the standard model with m_Z = 93.3 GeV and $\sin^2\theta_W = 0.22$ predicts sizeable asymmetries, namely

$$A_{LR}^{--} = 0.35 \ , \ A_{RR}^{-+} = 0.17 \text{ and } A_{RL}^{-+} = 0.52 . \qquad (21)$$

Thus, the deviations eq.(20) from these expectations due to the presence of Z_2 are measurable if the experimental errors can be reduced to $\delta A/A \approx \pm 10\%$. In this case, the Z_2 boson can escape detection only if $m_{Z_2} \gtrsim 300$ GeV and $|\theta| \lesssim 2°$ as one sees from Fig. 5. However, the detection limit drops rapidly in case[13] such a precision cannot be attained or only at lower values of Q^2. Furthermore, in Fig. 5 one can clearly distinguish the regions in m_{Z_2} and θ where the change δA of the asymmetries mainly comes from Z_2-exchange (flat parts of the contours at small values of m_{Z_2} and $\theta \approx 0$) as opposed to the regions where the effects dominantly originate in Z-Z' mixing (steep part of the contours at large values of m_{Z_2} and $\theta \neq 0$). Hence, only for a relatively light Z_2 is δA sensitive to the particular properties of Z_2 and one can hope to discriminate its existence from other interpretations of a possible signal. Finally, increasing the c.m. energy of ep collisions beyond the HERA energy $\sqrt{s} = 314$ GeV does not drastically improve the discovery limits[17]. The reason is basically that the maximum momentum transfer which is experimentally accessible does not increase proportionally to $\sqrt{s}$ since the number of events drops rapidly with Q^2 .

Finally, the obvious way to search for new gauge bosons at hadron colliders is to follow the procedure which led to the discovery of the W and Z bosons at the CERN $\bar{p}p$ collider[18]. From the latter experience one can expect to reach boson masses of a few hundred GeV at the TEVATRON, whilst supercolliders such as the LHC and the SSC should open up the TeV mass range for investigation. This general conjecture has been corroborated by extensive and detailed phenomenological studies[19-27]. In particular, it does not appear too difficult to detect a new neutral boson produced via $q\bar{q}$ annihilation in the reaction $\overset{(-)}{p}p \to Z'X$ by reconstructing the Z' resonance from the leptonic decays $Z' \to e^+e^-$ and $\mu^+\mu^-$. Focussing again on the E_6 boson Z_2 chosen in this talk as an illustrative example and making the same assumptions on the masses of the non-standard fermions in the 27-plets of E_6 as in eqs.(13) and (14), one obtains[22]

$$B_{ll} = B(Z_2 \to l^+l^-) \approx \begin{cases} 3.7\,\% & \text{(A)} \\ 0.9\,\% & \text{(B)} \end{cases} \qquad (22)$$

for the branching fraction of $Z_2 \to l^+l^-$. Here and in what follows, the mixing angle θ is set to 0 as the main interest is on a very heavy Z_2 for which mixing must be small (see e.g. Fig.5). The Z_2(=Z') production cross section at the SSC including the branching ratio B_{ee} for the case eq.(22B) is plotted in Fig.6 as a function of the Z_2 mass. If one assumes that ten $Z_2 \to e^+e^-$ events per year of 10^7 sec are sufficient for discovery one arrives at the detection limits summarized in Table 2. In fact, these limits lie somewhat on the low side in the sense that for other models the same detection criterion yields larger mass values. For instance, a massive Z' boson with otherwise standard Z-like properties should be detectable up to $m_{Z'} \approx 200$ GeV at the CERN collider[8] and $m_{Z'} \approx 6.5$ TeV at the SSC[24]. In order to investigate further details such

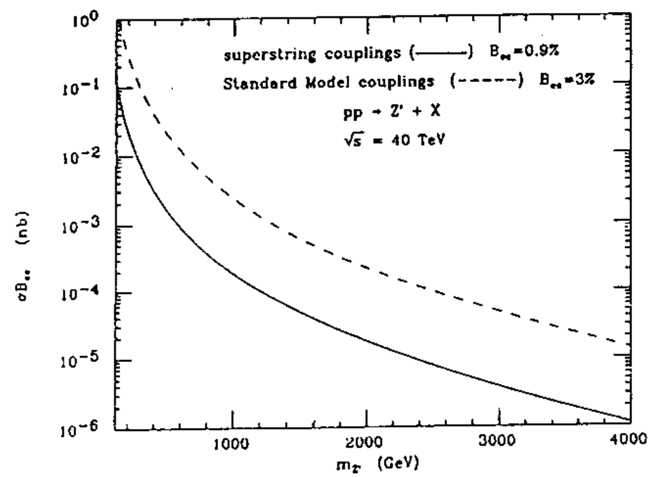

Fig.6 Total cross section for $pp \to Z_2X$, $Z_2 \to e^+e^-$ versus m_{Z_2}, at the SSC (taken from ref.22). The branching ratio B_{ee} = 0.9% corresponds to the assumption of three families of E_6 fermion 27-plets with no phase space suppression. The dashed curve shows the expectation for a massive standard Z-like boson.

as couplings of a new gauge boson to fermions one of course needs much higher statictics. Consequently, such theoretically very important studies are only possible for bosons with masses considerably below the limits mentioned above, for example, at the SSC[24,25] for masses below 1-2 TeV. Information on couplings can be extracted from measurements of asymmetries[24,25] and decay distributions[23,24,26,27]. The former method is applicable in cases in which the rapidity y of the boson and the scattering angle δ^* of the decay products in the boson rest frame are reconstructable from the observed final state as in $\overset{(-)}{p}p \to Z' + X$, $Z' \to l^+l^-$. Here, the forward-backward asymmetry

Table 2. Detection limits of Z_2 requiring a minimum of ten $Z_2 \to e^+e^-$ events per 10^7 sec for $B_{ee} = 0.9\%$.

collider	c.m. energy	luminosity	Z_2 mass
$\bar{p}p$ (CERN)[8]	630 GeV	10^{30} cm^{-2}s^{-1}	130 GeV
$\bar{p}p$ (Tevatron)[23]	2 TeV	10^{30} cm^{-2}s^{-1}	230 GeV
pp (SSC)[22]	40 TeV	10^{33} cm^{-2}s^{-1}	4 TeV

$$A_{FB}(y) = \left[\frac{d\sigma}{dy}\left(0 \le \delta^* \le \frac{\pi}{2}\right) - \frac{d\sigma}{dy}\left(\frac{\pi}{2} \le \delta^* \le \pi\right)\right] \Big/ \frac{d\sigma}{dy} \quad (23)$$

receives contribution proportional to $(L_l^2 - R_l^2)(L_q^2 - R_q^2)$ from each $q\bar{q}$ annihilation channel, where L_f and R_f denote the couplings of Z' to left- and right-handed fields, respectively. A_{FB} thus vanishes if $|L_f| = |R_f|$ as it is the case in a particular E_6 model where $E_6 \to SO(10) \times U(1)$ and and the neutral boson associated with the U(1) has identical couplings to all members of a fundamental 16-plet of SO(10), in particular to all 15 lepton and quark degrees of freedom of a standard family (see Table 1). In Fig. 7 a comparison is presented of the F-B asymmetries expected at the SSC for various gauge bosons, including the E_6 boson with the couplings listed in Table 1. Although it would only be possible to determine certain combinations of couplings from such a measurement[24], one clearly can distinguish the models given a sufficient number of events. The problem is more difficult if some of the decay products of a new gauge boson

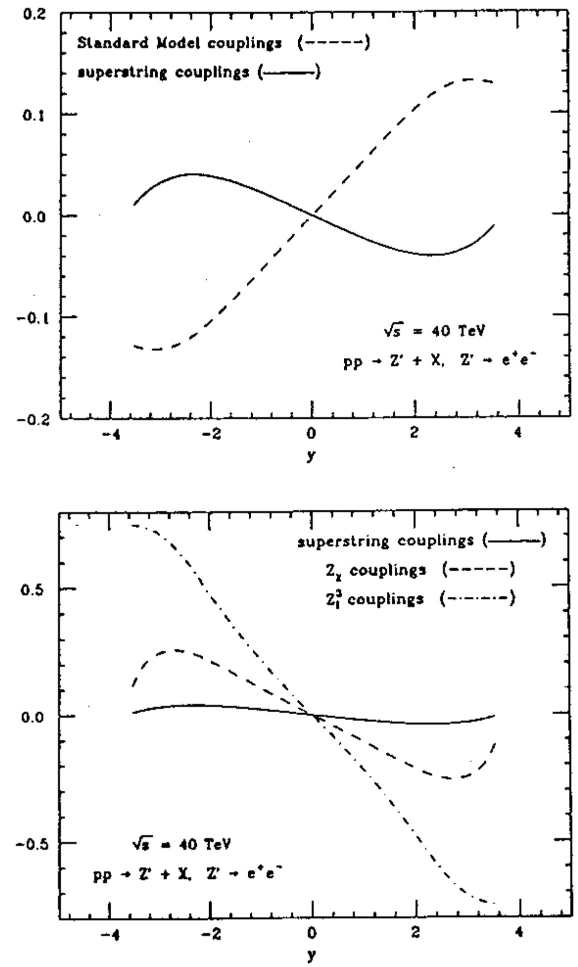

Fig.7 Forward-backward asymmetry $A_{FB}(y)$ defined in eq.(23) versus the boson rapidity in the reaction $pp \to Z'$, $Z' \to e^+e^-$ at $\sqrt{s}$ = 40 TeV (taken from ref.22). Compared are expectations for various neutral bosons with $m_{Z'}$ = 1 TeV, including the E_6 boson Z_2 (full curves) and a massive standard Z-like boson (dashed curve in the upper plot).

are invisible. This usually happens in decays of charged bosons into ordinary and/or new charged (L) and neutral (N) leptons, $W' \to LN$. Also in this case there are several ways to obtain at least partial information on the couplings, for example, by

(i) measuring the p_T distributions of the charged decay products of the τ-lepton[26] in the reactions $\overset{(-)}{p}p \to W'X$; $W' \to \tau N$; $\tau \to \nu_\tau X$ with X = $e\nu_e$, $\mu\nu_\mu$, π, ρ, and by

(ii) studying and preferably reconstructing the decay modes of new heavy leptons[27] L and/or N.

These tests play a particularly important role[24] in distinguishing W_L' from W_R'. I would just like to mention the striking signal which arises from $W_R \to eN_R$ in case N_R is a right-handed Majorana neutrino thus decaying with equal probability into $e^+ + X$ and $e^- + X$.

To summarize, at present there is no experimental evidence for gauge interactions beyond the strong and electroweak interactions of the $SU(3)_c \times SU(2)_L \times U(1)_Y$ standard model. On the other hand, extensions of the standard gauge group are possible, more or less plausible and suggested by superstring, grand-unified, horizontal and left-right symmetric models, to mention the most popular schemes. Present -day low-energy experiments permit the existence of new gauge bosons associated with such extensions with masses as low as 100-300 GeV and small mixing with the standard W and Z bosons[2,8]. Stronger, but also more model-dependent bounds, are obtained for a charged boson coupled to right-handed currents[1,2], $m_{W_R} \gtrsim 2$ TeV and $|\theta| < 0.3^o$, and for horizontal bosons mediating flavour-changing neutral transitions[24,28], $m_{X_h} >$ 5-100 TeV. It is an obvious and important task at future high energy accelerators to continue the seach for new gauge bosons and new currents involving known fermions and possibly also new exotic particles. In general, the presence of a new gauge boson may lead to observable changes of standard model relations due to mixing with the W or Z boson and to new effective interactions induced by virtual exchange, or it may be discovered by direct resonance production. On principle, ep collisions can only provide signals of the former kind. Although one can put stringent bounds on a given model if no effect is found, it is rather difficult to attribute an observed effect to a particular gauge boson and to

exclude other interpretations. Only for sufficiently light bosons and correspondingly large exchange effects does one have a realistic chance. At HERA ($\sqrt{s}$ = 314 GeV) this mass range is limited to 200-500 GeV depending on the particular model considered. Similar remarks and detection limits apply to e^+e^- annihilation at LEP I and SLC ($\sqrt{s} \approx m_Z$) and, given the present bounds, very likely also at LEP II ($\sqrt{s} \lesssim 200$ GeV). Complementary, in $\bar{p}p$ collisions at the Tevatron ($\sqrt{s}$ = 2 TeV) one can produce and detect new gauge bosons with masses less than 200-300 GeV. The above mass limits roughly characterize the prospects of detecting new gauge bosons in the foreseeable future. Considerable higher masses in the TeV range would then get in experimental reach at a e^+e^- linear-collider such as CLIC ($\sqrt{s} \sim 2$ TeV) or at $\overset{(-)}{p}p$ colliders such as LHC ($\sqrt{s} \approx$ 10-20 TeV) and SSC ($\sqrt{s} \sim 40$ TeV). For example, at the SSC one could discover new gauge boson with masses up to 3-8 TeV and at least partially determine their couplings to fermions for masses less than 1-2 TeV. On the whole, pp colliders in the multi-TeV range and with high luminosity $\mathcal{L} \approx 10^{33}$ $cm^{-2}s^{-1}$ promise the most powerful and direct way to search for possible extensions of the standard gauge structure.

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