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ABSTRACT

We study the prospects for detecting a new Z' boson in collisions of an electron or positron beam of LEP with a proton beam of the LHC. It is assumed that the Z' originates from a broken E_6 symmetry as suggested by superstring phenomenology. Particular sensitive tests would be provided by asymmetry measurements using longitudinally polarized $e^{\pm}$ beams. We present a detailed analysis of the deviations in neutral current asymmetries from the Standard Model predictions for three specific models and estimate discovery limits for the Z'.

1. INTRODUCTION

Many attempts to solve the puzzles of the standard $SU(3)_C \times SU(2)_L \times U(1)_Y$ model imply the existence of heavy vector bosons in addition to the observed W and Z bosons. Well-known examples are Left-Right Symmetric and Composite Models. More recently, it has been argued that extra neutral bosons may occur in the low energy limit of Superstring Theories [1,2], a conjecture which can be tested in accelerator experiments. In the simplest schemes of this kind one expects just one new Z' boson associated with an additional $U(1)$ gauge symmetry that may directly result from compactification of the heterotic $E_8 \times E_8'$ superstring at the Planck scale, or remain after further symmetry breaking at intermediate scales. Although this possibility is very speculative, it represents an interesting case for phenomenological studies.

Adopting the superstring-inspired scenario $E_8 \times E_8' \to G[\subset E_6] \supseteq SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ and assuming the $U(1)_{Y'}$ to be broken at a scale of $O(1\ TeV)$, we have investigated the prospects for the detection of the $U(1)_{Y'}$ gauge boson Z' in ep collisions at TeV energies. Current experimental limits [3] permit the existence of certain types of Z' with masses as low as

$$m_{Z'} \geq (110 - 150)\, GeV. \tag{1}$$

Yet, direct production and detection of the Z' in the process $ep \to eZ'X$ seems to be difficult even for such light masses. This follows from the relatively low cross-sections estimated for the production of the standard Z in $ep \to eZX$ [4], and from the fact that the Z' is expected to couple more weakly to the ordinary leptons and quarks than the Z. Since we want to find out discovery limits for the Z', we are mainly interested in heavier masses. Therefore, we have concentrated on indirect searches for the Z' in the neutral current (NC) scattering processes $e^{\pm}p \to e^{\pm}X$. It turns out that the effects due to the Z' in the inclusive NC cross-sections are also difficult to observe because of large contributions from photon exchange and the weak Z' couplings. The most sensitive tests seem to be provided by asymmetry measurements, similarly as in searches for other new physics phenomena in ep collisions [5]. Assuming the availability of longitudinally polarized $e^{\pm}$ beams, we shall present a detailed analysis of the changes to the various NC asymmetries induced by Z' bosons with different couplings corresponding to three specific choices for the $U(1)_{Y'}$ [6]. From the results of this study and estimates of the expected statistical errors in asymmetry measurements one can infer approximate detection limits.

For the ep c.m. energy and luminosity we have assumed the following values:

$$\begin{array}{lll} \text{(I)} & \sqrt{s} = 1.4\, TeV \quad \text{and} & L = 10^{32}\, cm^{-2}s^{-1}, \\ \text{(II)} & \sqrt{s} = 1.8\, TeV \quad \text{and} & L = 10^{31}\, cm^{-2}s^{-1}. \end{array} \tag{2}$$

These options exist in collisions of a $(50-100)\, GeV$ electron or positron beam of LEP with a 8 TeV proton beam of the hadron collider in the LEP tunnel (LHC) as dicussed at this workshop [7]. However, since polarized $e^{\pm}_{L,R}$ beams, being an essential tool in the searches proposed, are more likely to be available at the lower LEP I energy than at LEP 200, we shall almost exclusively show results for the option (I). A brief summary of our work can be found in the report to this workshop by J. Ellis and F. Pauss [2].

2. NEUTRAL CURRENT INTERACTIONS IN A $SU(2)_L \times U(1)_Y \times U(1)$ MODEL

We first give a brief description of the neutral current interactions in an electroweak model that has one additional $U(1)_{Y'}$ gauge symmetry beyond the standard $SU(2)_L \times U(1)_Y$ gauge group, pointing out the main consequences of the presence of a new Z' boson associated with $U(1)_{Y'}$. The effective neutral current lagrangian of such a model can be written in the form

$$\mathcal{L} = eJ^{\mu}_{em}A_{\mu} + \frac{g_L}{\cos\theta_W}J^{\mu}_{Z}Z_{\mu} + g_{Y'}J^{\mu}_{Z'}Z'_{\mu}, \tag{3}$$

where e, g_L and $g_{Y'}$ denote the electromagnetic, $SU(2)_L$ and $U(1)_{Y'}$ gauge couplings, respectively, and θ_W is the Weinberg angle relating e, g_L and the $U(1)_Y$ coupling g_Y: $e = g_L \sin\theta_W = g_Y \cos\theta_W$. The currents coupled to the photon field A_μ, the ordinary vector boson Z_μ and the new boson Z'_μ may be expressed as follows:

$$J^{\mu}_{em} = \sum_f \bar{f}\gamma^{\mu}Q_f f, \quad J^{\mu}_{Z} = \sum_f \bar{f}\gamma^{\mu}(v_f - a_f\gamma_5)f, \quad J^{\mu}_{Z'} = \sum_f \bar{f}\gamma^{\mu}(v'_f - a'_f\gamma_5)f, \tag{4}$$

with

$$v_f = \tfrac{1}{2}T_{3f} - \sin^2\theta_W Q_f, \quad a_f = \tfrac{1}{2}T_{3f}; \quad v'_f = \tfrac{1}{2}(Y'_{f_L} + Y'_{f_R}), \quad a'_f = \tfrac{1}{2}(Y'_{f_L} - Y'_{f_R}), \tag{5}$$

Q_f, T_{3f} and $Y'_{f_{L,R}}$ being the e.m. charge (with the convention $Q_e = -1$), the third component of the weak isospin and the $U(1)_{Y'}$ charges of a fermion f ($f_{L,R} = \frac{1}{2}(1 \mp \gamma_5)f$), respectively.

The weak bosons $W^\pm$, Z and Z' acquire masses through spontaneous breakdown of $SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ to $U(1)_{em}$. In general, the neutral bosons Z and Z' mix and form the mass eigenstates

$$Z_1 = Z\cos\theta + Z'\sin\theta, \quad Z_2 = -Z\sin\theta + Z'\cos\theta. \tag{6}$$

Evidently, the state Z_1 with the lower mass eigenvalue m_{Z_1} is to be identified with the already observed neutral boson. However, because of mixing the properties of Z_1differ somewhat from the properties of the Z boson of the Standard Model. Firstly, m_{Z_1} is lighter than m_Z as can be seen from the inequality

$$m_Z^2 = m_{Z_1}^2 \cos^2\theta + m_{Z_2}^2 \sin^2\theta \geq m_{Z_1}^2 \tag{7}$$

implied by eq. (6). Secondly, the Weinberg angle θ_W defined by the gauge couplings g_L and g_Y or, equivalently, by

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \tag{8}$$

deviates from the angle $\overline{\theta}_W$ obtained from the W and Z mass ratio:

$$\sin^2\overline{\theta}_W \equiv 1 - \frac{m_W^2}{m_{Z_1}^2} \leq 1 - \frac{m_W^2}{m_Z^2} \equiv \sin^2\theta_W. \tag{9}$$

Here, m_W denotes the standard W mass and m_Z is as given in eq.(7). The relation (8) is known to hold if the Higgs fields responsible for spontaneous symmetry breaking are $SU(2)_L$ doublets and singlets. Thirdly, the currentJ_1 which couples to Z_1 differs from the usual neutral current J_Z. This is explicitly seen by rewriting the lagrangian (3) in terms of Z_1 and Z_2:

$$\mathcal{L} = eJ^\mu_{em}A_\mu + \frac{e}{\sin\theta_W\cos\theta_W}(J_1^\mu Z_{1\mu} + J_2^\mu Z_{2\mu}), \tag{10}$$

with

$$J_1^\mu = \cos\theta\, J_Z^\mu + \frac{g_{Y'}\cos\theta_W}{g_L}\sin\theta\, J_{Z'}^\mu = \sum_f \overline{f}\gamma^\mu(v_{1f} - a_{1f}\gamma_5)f \tag{11}$$

$$J_2^\mu = -\sin\theta\, J_Z^\mu + \frac{g_{Y'}\cos\theta_W}{g_L}\cos\theta\, J_{Z'}^\mu = \sum_f \overline{f}\gamma^\mu(v_{2f} - a_{2f}\gamma_5)f. \tag{12}$$

The effective vector and axial vector couplings v_{if} and a_{if} can be obtained by substituting eq.(5) in

$$\begin{pmatrix} v_{1f} \\ v_{2f} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} v_f \\ g_{Y'}\cos\theta_W v'_f/g_L \end{pmatrix},$$
$$\begin{pmatrix} a_{1f} \\ a_{2f} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} a_f \\ g_{Y'}\cos\theta_W a'_f/g_L \end{pmatrix}. \tag{13}$$

In ep collisions one can thus distinguish two effects arising from the presence of a second neutral boson: modifications from the standard NC couplings and relations due to

$Z - Z'$ mixing, and additional contributions to $ep \to eX$ from Z_2 exchange. In the limit $m_{Z_2} \to \infty$, $\theta \to 0$ and $m_{Z_1} \to m_Z$ so that one recovers the Standard Model expectations. The allowed values of m_{Z_2} and θ are already restricted by W and Z mass measurements (mixing effects) and by low-energy NC-data (mixing and exchange effects) as shown later for specific models [3].

3. EP CROSS-SECTIONS AND ASYMMETRIES

From eq.(10-13) it is straightforward to calculate the NC cross-sections for polarized $e^{\mp}_{L,R}p$ scattering. Using $Q^2 = -k^2$ and $x = -k^2/2pk$ as independent variables where k is the four-momentum of the virtual bosons and p is the incoming proton momentum, one can write the inclusive differential cross-section for incident $e^-_{L,R}$ as follows:

$$\frac{d\sigma(e^-{}_{L,R})}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left((1+(1-y)^2)F_2^{L,R}(x,Q^2) + (1-(1-y)^2)xF_3^{L,R}(x,Q^2)\right). \tag{14}$$

Here, $y = Q^2/xs$ and $\sqrt{s}$ is the total c.m. energy. The structure functions $F_2^{L,R}$ and $xF_3^{L,R}$ are given by

$$F_2^{L,R}(x,Q^2) = \sum_f \{xq_f(x,Q^2) + x\overline{q}_f(x,Q^2)\}\tilde{F}_{2f}^{L,R}(Q^2), \tag{15}$$

$$xF_3^{L,R}(x,Q^2) = \sum_f \{xq_f(x,Q^2) - x\overline{q}_f(x,Q^2)\}\tilde{F}_{3f}^{L,R}(Q^2), \tag{16}$$

where $q_f(x,Q^2)$ and $\overline{q}_f(x,Q^2)$ are the quark and antiquark distribution functions of the proton, and

$$\begin{aligned}\tilde{F}_{2f}^{L,R}(Q^2) &= Q_f^2 + \textstyle\sum_{i=1}^2\{(v_{ie} \pm a_{ie})^2(v_{if}^2 + a_{if}^2)P_i{}^2 - 2Q_f(v_{ie} \pm a_{ie})v_{if}P_i\} \\ &\quad +2(v_{1e} \pm a_{1e})(v_{2e} \pm a_{2e})(v_{1f}v_{2f} + a_{1f}a_{2f})P_1P_2, \text{ and}\end{aligned} \tag{17}$$

$$\begin{aligned}\tilde{F}_{3f}^{L,R}(Q^2) &= \pm 2\{\textstyle\sum_{i=1}^2\left((v_{ie} \pm a_{ie})^2 v_{if}a_{if}P_i{}^2 - Q_f(v_{ie} \pm a_{ie})a_{if}P_i\right) \\ &\quad +(v_{1e} \pm a_{1e})(v_{2e} \pm a_{2e})(v_{1f}a_{2f} + a_{1f}v_{2f})P_1P_2\}\end{aligned} \tag{18}$$

are effective charge coefficients containing the vector and axial vector couplings defined in eq.(13). The Z_1 and Z_2 propagators are absorbed in the factors

$$P_i = Q^2/\left(\sin^2\theta_W \cos^2\theta_W(Q^2 + m_{Z_i}{}^2)\right). \tag{19}$$

The corresponding $e^+_{L,R}p$ cross-sections follow from eq.(14) by the replacements

$$F_2^{L,R} \to F_2^{R,L} \quad \text{and} \quad xF_3^{L,R} \to -xF_3^{R,L}. \tag{20}$$

The individual contributions from γ, Z_1 and Z_2 exchange and the interference terms can easily be recognized in eqs.(17) and (18).

Later on, we shall mainly deal with NC asymmetries. These are defined, generically, by the ratio

$$A(e_1 - e_2) = \frac{\tilde{\sigma}(\epsilon_1) - \tilde{\sigma}(\epsilon_2)}{\tilde{\sigma}(\epsilon_1) + \tilde{\sigma}(\epsilon_2)} \tag{21}$$

where $\tilde{\sigma}(e_i)$ with $e_i = e^{\mp}_{L,R}$ stands for the differential cross-sections $d\sigma(e_i)/dxdQ^2$ described above. Sometimes we shall also consider asymmetries integrated over x in which case $\tilde{\sigma}(e_i) \equiv d\sigma(e_i)/dQ^2$. In total, one can construct six different asymmetries: the polarization asymmetries $A(e^-_L - e^-_R)$ and $A(e^+_L - e^+_R)$, the charge asymmetries $A(e^-_L - e^+_L)$ and $A(e^-_R - e^+_R)$, and the mixed asymmetries $A(e^-_L - e^+_R)$ and $A(e^-_R - e^+_L)$.

4. SPECIFICATION OF Z'-MODELS

We have chosen to study a class of models for a new Z' boson which is suggested by superstring phenomenology [1,2]. Roughly speaking, compactification of the heterotic $E_8 \times E'_8$ superstring in 10 dimensions may lead to a supersymmetric E_6 theory in 4 dimensions with the E_6 symmetry broken to some subgroup G at the Planck scale. If there is no further symmetry breaking at intermediate scales, that is if G is the low energy group, it must necessarily be bigger than the gauge group of the Standard Model. This leaves $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'} = G \subset E_6$ as the minimal low energy theory containing the Standard Model. In case G is some bigger subgroup of E_6 we simply consider $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ as the result of intermediate stages of symmetry breaking. Finally, it is assumed that the extra $U(1)_{Y'}$ breaks down at a scale of $O(1\ TeV)$ in which case the Z' may acquire a mass $m_{Z'} \leq O(1\ TeV)$.

However, there is still an infinite number of possible $U(1)$ subgroups of E_6 which may play the role of the additional low energy gauge group $U(1)_{Y'}$. The point is that E_6 has rank 6 and thus contains two $U(1)$'s in addition to $SU(3)_C \times SU(2)_L \times U(1)_Y$ which has rank 4. Decomposing E_6 as indicated below,

$$\begin{aligned} E_6 \quad &\subset SO(10) \times U(1)_\psi \subset SU(5) \times U(1)_\chi \times U(1)_\psi \\ &\subset SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi , \end{aligned} \tag{22}$$

one can think of $U(1)_{Y'}$ as a linear combination of $U(1)_\chi$ and $U(1)_\psi$ [8]. More physically, the Z' boson associated with $U(1)_{Y'}$ can be represented by

$$Z'^{\mu} = Z^\mu_\psi \cos\alpha + Z^\mu_\chi \sin\alpha \tag{23}$$

where Z^μ_ψ and Z^μ_χ are the $U(1)_\psi$ and $U(1)_\chi$ gauge fields, and the angle α specifies a particular model. Moreover, the effective $U(1)_{Y'}$ gauge coupling takes the value

$$g_{Y'} = \sqrt{\frac{5}{3}} \frac{e}{\cos\theta_W} \tag{24}$$

normalized 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 $g_L = e/\sin\theta_W$.

The assignment of the new $U(1)_{Y'}$ charges to the fermions is now fixed by eqs.(23) and (24) as explained below. The 15 helicity components of a standard lepton and quark family form, together with new fermion species, a fundamental 27-plet of E_6 which contains the following $(SO(10), SU(5))$-representations.

$$\underline{27} = (\underline{16}, \underline{10} + \underline{5}^* + \underline{1}) + (\underline{10}, \underline{5} + \underline{5}^*) + (\underline{1}, \underline{1}). \tag{25}$$

The known fermions $\{u_L, d_L; u_L^c, e_L^c\}$ and $\{d_L^c; \nu_L, e_L\}$ fill the $(\underline{16},\underline{10})$ and $(\underline{16},\underline{5}^*)$ multiplets, respectively. Corresponding assignements hold for the heavier families. Parametrizing the new $U(1)_{Y'}$ charges of the fermions in accordance with eqs.(22) and (23), one has

$$Y'_f = Y_f^\psi \cos\alpha + Y_f^\chi \sin\alpha \tag{26}$$

where $Y_f^\psi[Y_f^\chi]$ denote the $U(1)_\psi[U(1)_\chi]$ charges [8] given below for the multiplets quoted in eq.(25):

E_6	$\underline{27}$					
$SO(10)$	$\underline{16}$			$\underline{10}$		$\underline{1}$
$\sqrt{6}Y^\psi$	$1/2$			-1		2
$SU(5)$	$\underline{10}$	$\underline{5}^*$	$\underline{1}$	$\underline{5}$	$\underline{5}^*$	$\underline{1}$
$\sqrt{10}Y^\chi$	$1/2$	$-3/2$	$5/2$	-1	1	0

The supersymmetric counterparts of the fermions play no role for the later discussion and are therefore not considered further. Finally, the Higgs fields also belong to a $\underline{27}$-plet of E_6 which contains only $SU(2)_L$ doublets and singlets. Hence, the relation (8) is fullfilled in this class of models.

Numerically, we have investigated the following three examples [2,6]:

$$\begin{array}{llll} \text{model A:} & \cos\alpha = \sqrt{\frac{5}{8}} & , \quad \sin\alpha = \sqrt{\frac{3}{8}} & , \\ \text{model B:} & \cos\alpha = 0 & , \quad \sin\alpha = 1 & , \\ \text{model C:} & \cos\alpha = -\sqrt{\frac{15}{16}} & , \quad \sin\alpha = \sqrt{\frac{1}{16}} & . \end{array} \tag{27}$$

Model A is unique in the sense that it corresponds to the minimal scenario $G = SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ considered above, while models B and C involve symmetry breaking at intermediate scales triggered by a $(\underline{1},\underline{1})$ and a $(\underline{16},\underline{1})$ scalar field in the case of B and C, respectively. The corresponding hypercharges Y' can be obtained from eq.(26). Since the exotic fermions in the fundamental $\underline{27}$-representation of E_6 (see eq.(25)) do not participate in $ep \to eX$, we only state the charges of the ordinary leptons and quarks:

$$\begin{array}{lcllll} Y'(u_L, d_L; u_L^c, e_L^c) & = & 1/\sqrt{15}\ \ (\text{A}), & 1/2\sqrt{10}\ \ (\text{B}), & -1/2\sqrt{10}\ \ (\text{C}), \\ Y'(d_L^c; \nu_L, e_L) & = & 1/2\sqrt{15}\ \ (\text{A}), & -3/2\sqrt{10}\ \ (\text{B}), & -1/\sqrt{10}\ \ (\text{C}), \end{array} \tag{28}$$

and correspondingly for the heavier families. Obviously, the new hypercharges of right-handed fermions entering eq.(5) are given by $Y'_{f_R} = -Y'_{f_L^c}$. It should further be noted that for model A and B our charge assignment is exactly the same as the one used in ref.[2], while for model C there is a difference in the overall sign. This difference has no consequences other than a relative sign in the mixing angle θ for the two conventions.

5. NUMERICAL RESULTS

We are now ready to illustrate the sensitivity of searches for new Z' bosons in ep collisions at LEP-LHC. For reasons explained in the introduction, we shall completely rely on asymmetry measurements with polarized $e^{\mp}_{L,R}$ beams and a total integrated luminosity of $\int Ldt = 1\ fb^{-1}$ per year ($250\ pb^{-1}$ for each polarization state) at the c.m. energy $\sqrt{s} = 1.4\ TeV$. The numerical analysis is carried out according to the following strategy [9]. Apart from the Z' couplings specified in eqs.(24) and (28), the modified NC interactions involve four more parameters: the vector boson masses m_{Z_1} and m_{Z_2}, the Z-Z' mixing angle θ and the Weinberg angle θ_W. The lower mass m_{Z_1} is assumed to be known experimentally with great precision (e.g. from measurements at LEP). We have taken the value $m_{Z_1} = 93.3\ GeV$. Furthermore, using the constraint (8) and substituting m_Z from eq.(7) and $m_W = 38.65\ GeV/\sin\theta_W$, one obtains the Weinberg angle as a function of m_{Z_2} and θ. The above relation for m_W includes the standard radiative corrections [10] but neglects the contributions from the new particles in our models, an approximation which suffices for the present purposes. Finally, m_{Z_2} and θ (being related to uncertain vacuum expectation values of Higgs fields [2,11]) are considered as essentially free parameters. We then investigate deviations from the Standard Model expectations due to the Z' in the (m_{Z_2}, θ)-plane for the models A, B, and C defined in the last chapter. The remaining numerical input is $\alpha = 1/137$ for the fine structure constant and set I of ref.[12] for the quark and antiquark distribution functions of the proton.

Quite generally, one can say that the Z' bosons considered in the present study are more difficult to detect in NC ep scattering than a Z' of the kind expected in some Left-Right Symmetric Models, or a simple repetition of the standard Z with a heavier mass [5]. Reasons for that are the comparatively weak Z' couplings and destructive interferences in the contributions to $ep \to eX$ from γ, Z_1 and Z_2 exchange. For example, we have compared the NC cross-sections for model A with the Standard Model predictions and find that the effects from Z_2 ($= Z'$ for $\theta = 0$) do not exceed a few per cent even for m_{Z_2} as low as 200 GeV and for very large values of Q^2. Quantitatively, the unpolarized cross-section for $e^-p \to e^-X$ integrated over x and $Q^2 \geq m_{Z_2}^2 = 4 \times 10^4\ GeV^2$ *decreases* by $\Delta\sigma/\sigma \simeq 3\%$ relative to the cross-section $\sigma_{SM}(e^-p \to e^-X; Q^2 \geq 4 \times 10^4\ GeV^2) \simeq 5.6pb$ expected in the Standard Model. Although the effect is still larger than the statistical error of about 1.3% corresponding to 5600 events for $\int Ldt = 1\ fb^{-1}$, it is probably drowned in systematic uncertainties. The changes in the unpolarized NC cross-sections for $m_{Z_2} \simeq 500\ GeV$ are definetely not observable.

The prospects for detecting the Z' improve considerably, if polarized $e^{\pm}_{L,R}$ beams are available. One can then search for effects in the NC asymmetries introduced in eq.(21). These are more sensitive observables and have the further advantage that one can expect cancellations of systematic errors in the experimental determination of ratios of cross-sections. In Fig. 1 we present a comprehensive survey of the sensitivity of the six different asymmetries to the Z' for models A, B and C. Shown are the contours in the (m_{Z_2}, θ)-plane for which the Standard Model asymmetries $A_{SM}(e_1 - e_2)$ differ from the asymmetries $A(e_1 - e_2)$ predicted in the two-Z models by a fixed amount $\delta A = |A(e_1 - e_2) - A_{SM}(e_1 - e_2)|$. For this illustration we have chosen a suitable kinematical point which is experimentally accessible with reasonable statistics. Asymmetry mesurements with a precision δA would allow to explore the regions in m_{Z_2} and θ outside the contours corresponding this particular value of δA. The following facts are noteworthy:

(1) The detection limits in m_{Z_2} and θ depend strongly on the Z' model as well as on the asymmetry considered.

(2) The sidewise boundaries in the contour-plots of Fig. 1 come mainly from effects due to Z-Z' mixing and constrain in particular θ, while the contributions to the asymmetries from

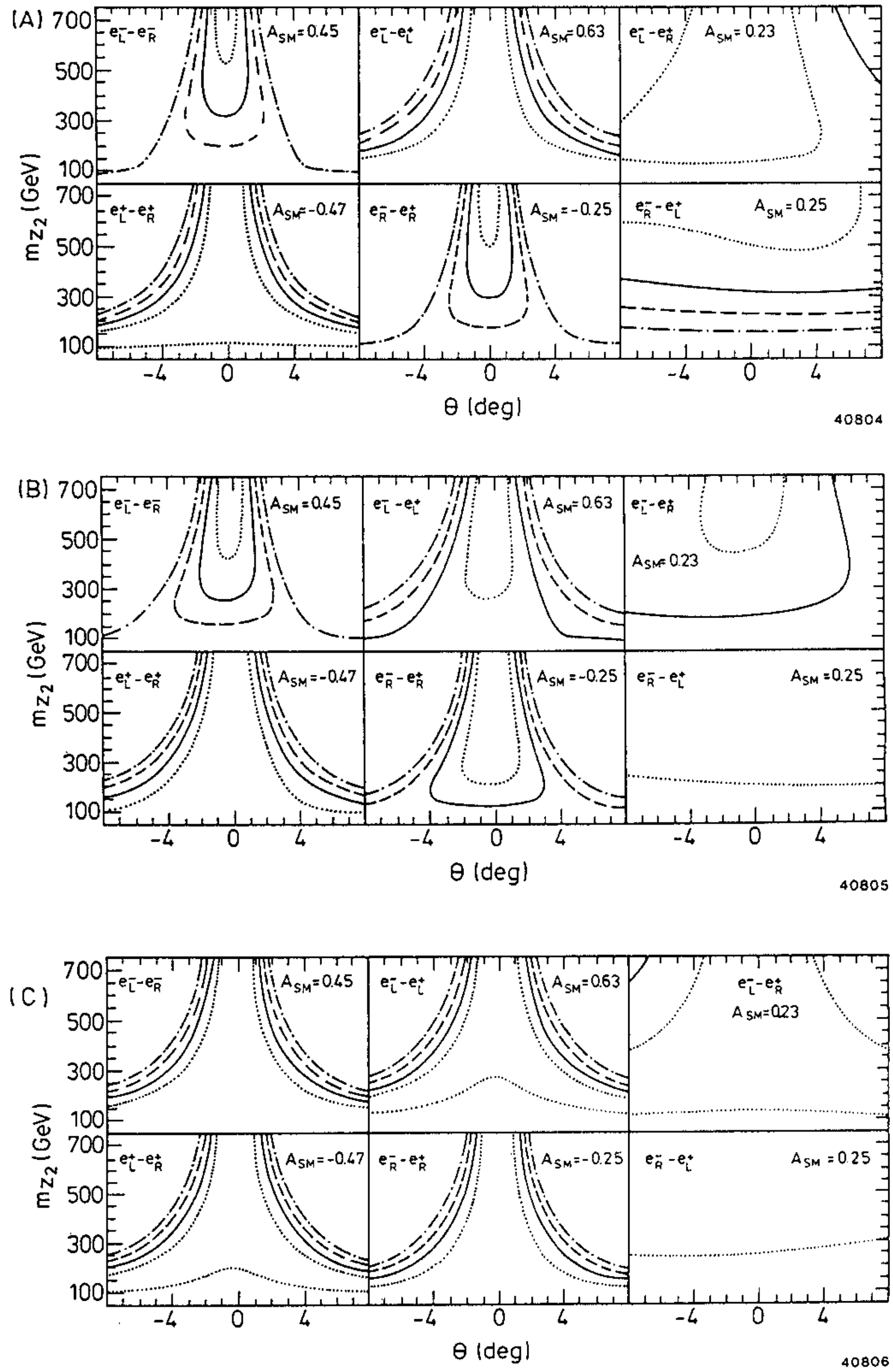

Fig. 1 Contour lines of $\delta A = |A(e_1 - e_2) - A_{SM}(e_1 - e_2)| = 0.02$ (dotted), 0.04 (full), 0.06 (dashed), 0.08 (dashed-dotted) in the (m_{Z_2}, θ)-plane for models (A), (B) and (C) at $\sqrt{s} = 1.4\ TeV, x = 0.05$ and $Q^2 = 7 \times 10^4\ GeV^2$. The Standard Model values A_{SM} of the NC asymmetries are also given.

Z_2 exchange lead to lower bounds on m_{Z_2} which vary only weakly with θ.
(3) Z-Z' mixing affects the polarization and charge asymmetries quite uniformly (apart from the sign of δA which is not shown in Fig. 1), while the mixed asymmetries are rather insensitive. Moreover, these effects are to a large extent model-independent as expected.
(4) In contrast, deviations in the asymmetries due to Z_2 exchange clearly discriminate between the models A, B and C as can be seen by comparing Figs. 1(A-C) for small mixing angles around $\theta = 0$.
The above results emphasize the importance of studying as many asymmetries as possible in order to optimize the sensitivity, to distinguish the existence of a new Z' from other possible sources of an effect which might be seen, and to determine some of the properties of the Z'. A glance at Fig. 1 shows which asymmetries are the most sensitive ones for models A, B and C. Similar studies for HERA energies can be found in refs.[9,11].

The drawback of such a comprehensive measurement is the necessity to share luminosity among $e^{\pm}_{L,R}p$ collisions. Fig. 2 illustrates the statistical significance one can expect for an integrated luminosity of $\int Ldt = 250\ pb^{-1}$ per polarization state, i.e. $1fb^{-1}$ in total, and 100% beam polarization. In this figure we compare the Standard Model asymmetry $A_{SM}(e^-_L - e^-_R)$ integrated over x with the corresponding asymmetries expected in model A for $\theta = 0$ and two $Z_2(= Z')$ masses. Of course, we have chosen the most sensitive asymmetry for this test. The statistical error in the bin $Q^2 = 6.3 \times 10^4\ GeV^2$ to $10^5\ GeV^2$ is $\delta A \simeq 0.03$ and decreases for lower Q^2 bins. We believe that systematic errors in the determination of the luminosity and beam polarization, and also theoretical uncertainties in the Standard Model predictions can be largely removed by comparing the data and the Standard Model in the low Q^2 region. One can then use the data at higher values of Q^2 to search for deviations with a sensitivity which is basically limited by statistical errors. In that case, an appropriate χ^2-analysis would increase the overall significance, e.g. in the last Q^2 bin to $\delta A \simeq 0.02$. If no effect is seen, one would thus be able to put the bound $m_{Z_2} \geq\ 500\ GeV$ at $\theta \simeq 0$ for model A as can be seen from Fig. 2. More generally, one could exclude the existence of the Z' with values of m_{Z_2} and θ outside the contours corresponding to $\delta A(e^-_L - e^-_R) \simeq 0.02$ in Fig. 1. The last statement also applies to the other models.

Before summarizing the detection limits found in the way explained above, we want to stress that luminosity has absolute priority over energy in searches for a Z'. This is substantiated in Fig. 3 which shows the same test as Fig. 2 except that the energy is increased to $\sqrt{s} = 1.8\ TeV$ and the luminosity is lowered to $\int Ldt = 25\ pb^{-1}$ per polarization state according to the energy-luminosity estimates [7] quoted in eq.(2). We are aware of the fact that polarization is unlikely to be available at the maximum ep energy, which does not hinder us to make the following point. A 10 times smaller luminosity than the one assumed in Fig. 2 would decrease the statistical significance of searches for the Z' in the range $Q^2 = 6.3 \times 10^4\ GeV^2$ to $10^5\ GeV^2$ to $\delta A \simeq 0.09$ or $\delta A \simeq 0.06$ after a more sophisticated χ^2-analysis. As a consequence, one would only be able to explore the regions in m_{Z_2} and θ corresponding to $\delta A \simeq 0.06$ in Fig. 1. In particular, for model A and $\theta \simeq 0$ one would obtain the much weaker lower bound $m_{Z_2} \geq 200\ GeV$ for the mass of the $Z_2(\simeq Z')$ as can be also guessed from Fig. 3.

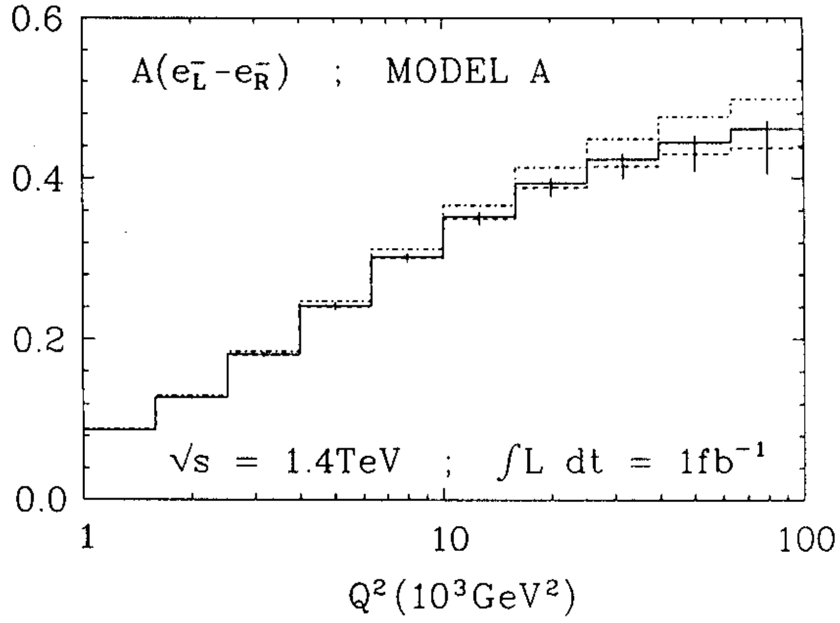

Fig. 2 Polarization asymmetry $A(e_L^- - e_R^-)$ integrated over x for model A assuming $\theta = 0$ and taking $m_{Z_2} = 200\ GeV$ (dashed-dotted) and 500 GeV (full), in comparison to the Standard Model prediction (dashed). The error bars indicate statistical errors for an integrated luminosity of 1 fb^{-1} shared equally among runs with $e_{L,R}^-$ and $e_{L,R}^+$ beams.

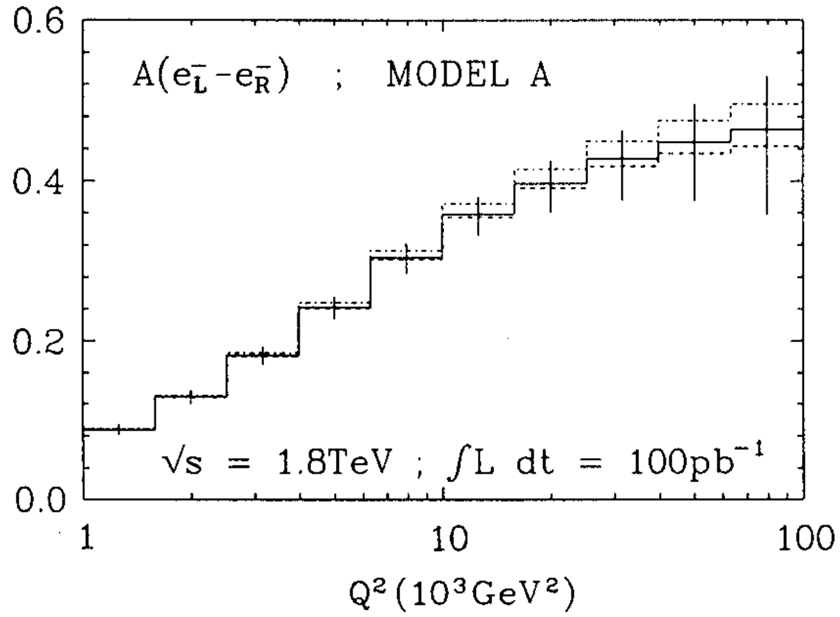

Fig. 3 Same as Fig. 2 but for a higher c.m energy and a lower luminosity.

6. SUMMARY

We have studied searches for a new Z' boson in ep collisions at $\sqrt{s} = 1.4\ TeV$ and $L = 10^{32}\ cm^{-2}s^{-1}$ which rely completely on asymmetry measurements with polarized $e^{\pm}_{L,R}$ beams. Such searches may be feasible at LEP-LHC operating in the ep mode. We have presented arguments which suggest that it should be possible to achieve an overall sensitivity to deviations of the asymmetries from the predictions of the Standard Model of about $\delta A = 0.02$ at $Q^2 \geq 6 \times 10^4\ GeV^2$. In that case one can reach the detection limits for models A and B plotted in Fig. 4. As obvious from Fig. 1C, model C is rather difficult to test. For comparison, Fig. 4 also shows the current boundaries in m_{Z_2} and θ for models A and B which practically exclude negative mixing angles.

As somewhat more conservative estimates, we quote below the lower bounds on m_{Z_2} at $\theta = 0$ which can be expected from asymmetry measurements with a precision $\delta A \simeq 0.04 - 0.02$:

model A: $m_{Z_2} \geq (300 - 500)\ GeV$,

model B: $m_{Z_2} \geq (250 - 400)\ GeV$,

model C: $m_{Z_2} \geq$ (no useful limit $- 250)\ GeV$.

Without polarized $e^{\pm}_{L,R}$ beams the prospects for detecting the Z' decrease drastically to the level of the present bounds. Hence, longitudinal polarization is mandatory for Z' physics at ep colliders [5].

Moreover, if a Z' boson exists in the mass ranges indicated above asymmetry measurements are very useful for establishing clear evidence by excluding other possible sources of the observed effect, and for determining some of the Z' couplings. The great sensitivity of the asymmetries to the Z' couplings is demonstrated in Fig. 5 for the superstring-inspired class of models considered in this work.

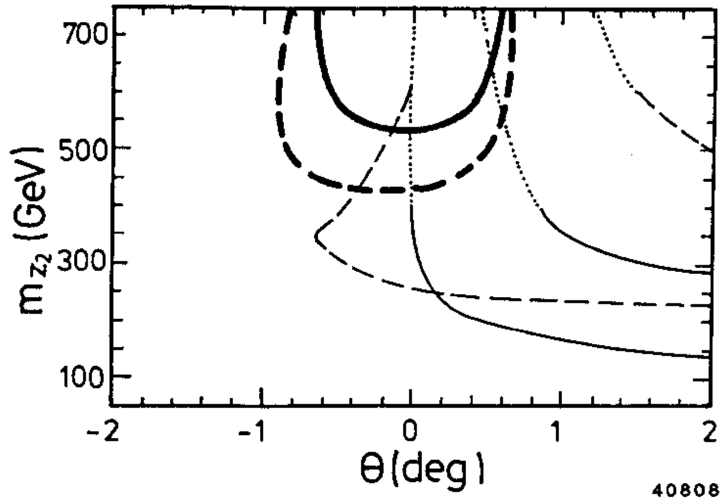

Fig. 4 Detection limits for models A (full) and B (dashed) expected from asymmetry measurements for a run of 1 fb^{-1}, using essentially $A(e_L^- - e_R^-)$. The thin full (model A) and dashed (model B) lines show the present bounds reported in ref.[3]. The dotted line is an extrapolation assuming $\theta \sim 1/m_{Z_2}$.

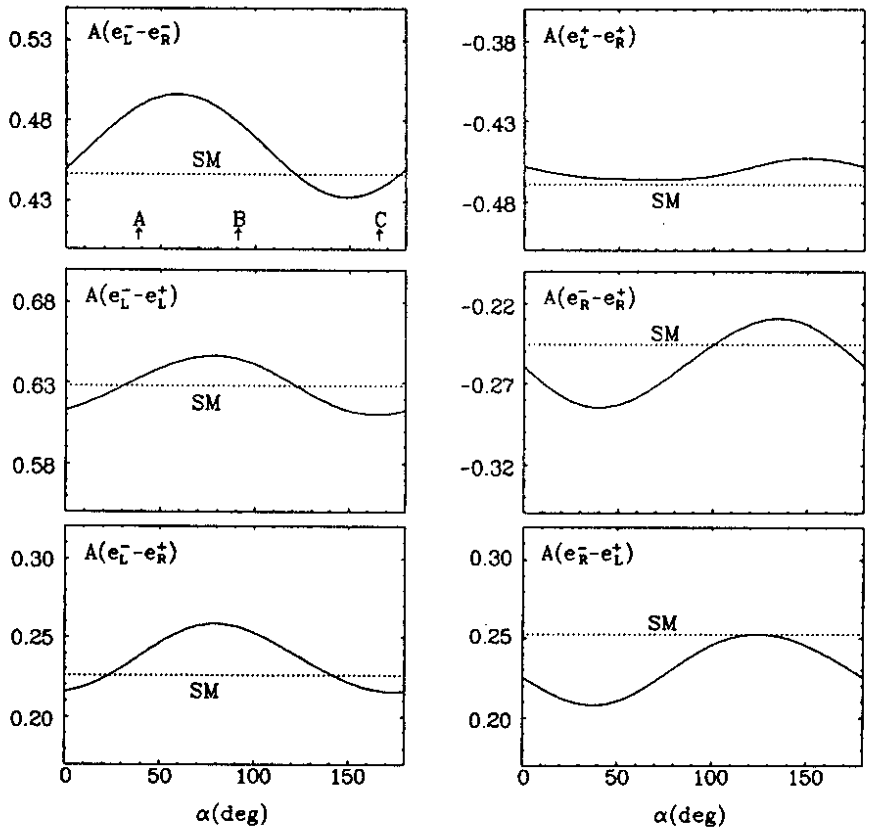

Fig. 5 Expected deviations from the Standard Model predictions (dotted) in the NC asymmetries for the present class of $SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ models at $\sqrt{s} = 1.4\,TeV, x = 0.05$ and $Q^2 = 7 \times 10^4\,GeV^2$. The angle α specifies a particular $U(1)_{Y'}$ and fixes the new hypercharges Y' (see chapter 4). Models A, B and C correspond to $\alpha = 37.8°, 90°$ and $165.5°$, respectively. The mixing angle θ is set to zero and $m_{Z'} = 300\,GeV$.

References

[1] For a review, see
R.D. Peccei, Proc. of the 23rd Int. Conf. on High Energy Physics, Berkeley, 1986, ed. S.C. Loken (World Scientific Pub. Co., Singapore, 1987) p. 3.

[2] J. Ellis and F. Pauss, Vol. I of these Proceedings, p. 80.

[3] U. Amaldi et al., Univ. of Pennsylvania preprint UPR-0331T (1987).

[4] G. Altarelli, G. Martinelli, B. Mele and R. Rückl, Nucl. Phys. B262 (1985) 204;
E. Gabrielli, Mod. Phys. Lett. A1 (1986) 465.

[5] R.J. Cashmore et al., Phys. Rep. 122 (1985) 275;
R. Rückl, Proc. of the ECFA-Workshop LEP 200, Aachen, 1986, DESY 87-021.

[6] F. Zwirner, Vol. II of these Proceedings.

[7] G. Brianti, Vol. I of these Proceedings, p. 6.

[8] D. London and J.L. Rosner, Phys. Rev. D34 (1986) 1530.

[9] F. Cornet and R. Rückl, Phys. Lett. 184B (1987) 263.

[10] W.J. Marciano and A. Sirlin, Phys. Rev. D22 (1980) 2695.

[11] V.D. Angelopoulos, J. Ellis, D.V. Nanopoulos and N.D. Tracas, Phys. Lett. 176B (1986) 203.

[12] D.W. Duke and J.F. Owens, Phys. Rev. D30 (1984) 49.