Identifying the origin of new gauge bosons at the Superconducting Super Collider

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(Received 12 August 1991)

We examine the ability of the detector of the Solenoidal Detector Collaboration (SDC) to identify the origin of a new neutral gauge boson Z_2 in the TeV mass range at the Superconducting Super Collider. Specifically, given the measurements of the Z_2 production cross section, width, and leptonic forward-backward asymmetry, together with their associated statistical and systematic errors, we address two related questions: (i) For two different extended electroweak models, up to what mass can their corresponding Z_2 bosons be distinguished, and (ii) how well can the Z_2 couplings be determined? Our calculations include $O(\alpha_s^2)$ QCD, as well as oblique electroweak radiative corrections to the above quantities, and allow for uncertainties due to structure functions, detector efficiencies, lepton identification, luminosity measurement errors, and finite lepton-pair mass resolution, using the specifications of the SDC detector. Nine distinct classes of extended electroweak models are investigated and results are obtained for integrated luminosities of 10^4 and 10^5 pb^{-1}.

PACS number(s): 13.85.Rm, 12.15.Cc, 14.80.Er

I. INTRODUCTION

Although the standard model (SM) is in excellent agreement with existing data once radiative corrections are included [1], it is commonly believed that new physics must exist in order to address the many questions that the SM leaves unanswered. A common prediction of many scenarios which go beyond the SM is the existence of at least one new neutral gauge boson (Z_2). During the next decade such a particle can be searched for in a number of ways, e.g., via direct production at the Fermilab Tevatron [2], through precision measurements [3] of the properties of the SM Z boson at the CERN e^+e^- collider LEP I, and by looking for possible deviations from SM expectations for neutral-current cross sections and asymmetries at the DESY *ep* collider HERA [4] and CERN LEP II [5]. Nevertheless, it is unlikely [6] that new gauge boson will show themselves at these colliders unless their masses are significantly below 1 TeV. To improve these search capabilities we therefore must wait until the advent of hadron supercolliders, such as the Superconducting Super Collider (SSC) and CERN Large Hadron Collider (LHC). Many studies have shown that both the SSC [7] and LHC [8] are excellent tools for cleanly producing new gauge bosons up to masses of several TeV. However, if a Z_2 is discovered, we will want to know more about it than its mere existence. What we will really want to learn is its origin, i.e., which Z_2 out of the plethora predicted by various models has been found. (Perhaps it may have nothing to do with *any* of the models that are presently on the market.)

In this paper we address the ability of a *real* SSC detector, that of the Solenoidal Detector Collaboration (SDC) to ascertain the specific extended electroweak model which is the source of the Z_2, once it has been discovered. Pioneering work was performed in this area at the 1990 Snowmass Workshop by Whisnant [9], but in a somewhat simplified context and without considering the characteristics of a specific detector such as the SDC. Our work examines the following related issues: (i) the SDC's capability of determining the various couplings of the Z_2, and (ii) the maximum value of the Z_2 mass for which adequate statistics exist to distinguish one extended model from another. This maximum value of the Z_2 mass will be denoted as the identification (ID) limit. Unlike e^+e^- machines, hadron colliders are limited to only a few measurable quantities with which the properties of new gauge bosons can be determined: namely, the mass (M_2), the width (Γ_2), production cross section (σ), and the leptonic forward-backward asymmetry ($A_{\rm FB}$). To answer the identification questions we need to know how well the SDC can measure the above quantities, as well as the theoretical uncertainties associated with comparing model predictions and data. The goal of the present work is not to be the final answer to the above questions, but to be a further step toward dealing with a realistic situation which may arise at the SSC.

The contents of this paper are as follows. In Sec. II the basic formalism for studying Z_2 production at *pp* colliders and the various extended electroweak models that we consider in our analysis are reviewed. The procedure that we have followed and the various input parameters that we have used in our analysis are given in Sec. III, as

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is a discussion of our results. Our summary, conclusions, and directions for future work are contained in Sec. IV.

II. BASIC FORMALISM

To lowest order in α_s and in the electroweak interactions, we are interested in the reaction $pp \to l^+l^-X$, which proceeds through the parton-level subprocess $q\bar{q} \to \gamma, Z_1, Z_2 \to l^+l^-$. Here, Z_1 is the neutral gauge boson of the SM as observed at LEP [10], i.e., $M(Z_1) \equiv M_1 = 91.174$ GeV and $\Gamma(Z_1) \equiv \Gamma_1 = 2.486$ GeV. The differential cross section for this subprocess is given by

$$\frac{d\sigma}{dM\,dy\,dz} = \epsilon_l K \frac{\pi\alpha^2}{3M^3} \sum_q [S_q G_q^+(1+z^2) + 2A_q G_q^- z] , \tag{2.1}$$

where $\alpha = \alpha(M_Z) \simeq \frac{1}{128}$, M is the final-state lepton-pair invariant mass, y is the rapidity of the outgoing leptons, $z \equiv \cos\theta_{ql^-}$,

$$G_q^{\pm} \equiv x_a x_b [q(x_a)\bar{q}(x_b) \pm \bar{q}(x_a) q(x_b)] ,$$

$$S_q \equiv \sum_{i,j} \left[\frac{g_i}{e}\right]^2 \left[\frac{g_j}{e}\right]^2 P_{ij}(M^2)(v_i v_j + a_i a_j)_q (v_i v_j + a_i a_j)_l , \tag{2.2}$$

$$A_q \equiv \sum_{i,j} \left[\frac{g_i}{e}\right]^2 \left[\frac{g_j}{e}\right]^2 P_{ij}(M^2)(v_i a_j + v_j a_i)_q (v_i a_j + v_j a_i)_l ,$$

with $x_{a,b} = Me^{\pm y}/\sqrt{s}$, $q(x_{a,b})$ are the quark distribution functions, and e is the electric charge of the proton. The fermionic couplings of the ith neutral gauge boson (where $i = 0$, 1, and 2 corresponds to the photon, Z_1, and Z_2, respectively) are defined as

$$\mathcal{L} = g_i \bar{f} \gamma_\mu (v_{if} - a_{if}\gamma_5) f Z_i^\mu , \tag{2.3}$$

and

$$P_{ij} \equiv M^4 \frac{(M^2 - M_i^2)(M^2 - M_j^2) + (M_i\Gamma_i)(M_j\Gamma_j)}{[(M^2 - M_i^2)^2 + (\Gamma_i M_i)^2][(M^2 - M_j^2)^2 + (\Gamma_j M_j)^2]} , \tag{2.4}$$

where Γ_i and M_i are the width and mass of the ith gauge boson, respectively. The factor K accounts for full QCD corrections, through $O(\alpha_s^2)$, to the production of lepton pairs with zero net transverse momentum, and depends on M^2 as well as the various experimental cuts (e.g., rapidity). We obtain our values for K from the program WZPROD of Hamberg, van Neerven, and Matsuura [11]. ϵ_l represents a generic experimental efficiency factor for the identification of a lepton pair and will be discussed further below.

Combining Eqs. (2.1)–(2.4) with our knowledge of the parton distribution functions, we calculate the quantities of interest following the work of the SDC [12] in our cuts and definitions. The Z_2 total production cross section σ is the integral of Eq. (2.1) over the regions $M_2 - \Gamma_2 \le M \le M_2 + \Gamma_2$, $-Y \le y \le Y$, and $-Z \le z \le Z$, where

$$\begin{aligned} Y &= \min[2.5, -\ln(M_2/\sqrt{s})] , \\ Z &= \min[\tanh(Y - |y|), 1] . \end{aligned} \tag{2.5}$$

To calculate the forward-backward asymmetry (A_{FB}), Eq. (2.1) is first integrated over the forward ($z > 0$) and the backward ($z < 0$) regions separately (subject to $|z| \le |Z|$) and then over y and M; the difference of the forward and backward cross sections divided by their sum then gives A_{FB}. Explicitly, the partially integrated quantities are defined as

$$\frac{d\sigma^{\pm}}{dM\,dy} \equiv \epsilon_A \left[\int_{z>0} \pm \int_{z<0}\right] \left[\frac{d\sigma}{dM\,dy\,dz}\right] dz , \tag{2.6}$$

so that

$$\sigma^{\pm} \equiv \epsilon_A \int dM \left[\int_{-y_{\min}}^{Y} \pm \int_{-Y}^{-y_{\min}}\right] \left[\frac{d\sigma^{\pm}}{dM\,dy}\right] dy . \tag{2.7}$$

The forward-backward asymmetry is then given by

$$A_{FB} = (\sigma^- / \sigma^+) . \tag{2.8}$$

In order to gain in statistics we follow Ref. [12] in our calculations and integrate M over the interval $0.75M_2 \le M \le 1.25M_2$, and integrate y over the region $y_{\min} \le |y| \le Y$ with Y given in Eq. (2.5). The additional $y_{\min}$ cut (as used by Ellpley and Miettinen [13] with $y_{\min} = 0.3$) is essentially a cut on the longitudinal momentum of the Z_2 and allows for the definition of the angle θ_{ql^-}. Note that we have also included an efficiency factor ϵ_A in the above equations, which accounts for the ability of the detector to correctly identify the electric charges of the produced leptons. Although it does not enter into the expression for A_{FB} explicitly, ϵ_A will be important in determining the statistical error in A_{FB} since σ^+ is directly related to the number of events in the relevant (M,y) regions which have their charges correctly identified.

In order to proceed further, we need to have a specific extended electroweak model in mind and choose a set of structure functions to perform the above integrations. We will return to this latter point below. For the benefit of the reader, we now briefly review the various models that we have chosen to examine. Although there are a very large number of extended models in the literature which predict the existence of a Z_2, we feel that the subclass of such models selected here is fairly representative of the group as a whole, although it is not exhaustive. The specific models we consider are the following.

(i) The effective rank-5 model (ER5M) originates [14] from the breaking of a superstring-inspired E_6 grand unified theory (GUT) via the chain $E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi \to SM \times U(1)_\theta$. Here $U(1)_\theta$ is a linear combination of $U(1)_\psi$ and $U(1)_\chi$ that remains unbroken at low energies. The Z_2 in this model has couplings of the form

$$\left[\frac{5x_W}{3}\right]^{1/2} \left[\frac{Q_\psi}{\sqrt{6}}\cos\theta - \frac{Q_\chi}{\sqrt{10}}\sin\theta\right] , \tag{2.9}$$

where θ is a free parameter which lies in the range $-90° \le \theta \le 90°$, $x_W \equiv \sin^2\theta_W$, and $Q_\psi(Q_\chi) = [1,1,1]([-1,3,-5])$ for the left-handed fermions in the **10**, $\bar{\mathbf{5}}$, and **1** of SU(5) contained in the usual **16** of SO(10). Specific models of interest in this category are model ψ (corresponding to $\theta = 0°$), model χ ($\theta = -90°$), model η ($\theta = \arcsin(\sqrt{3/8} \simeq 37.76°)$, which is the rank-5 model derived [15] directly from the flux breaking of superstring E_6 theories, and model I ($\theta = -\arcsin\sqrt{5/8} \simeq -52.24°$), where the Z_2 can be identified [16] as that which couples to the diagonal generator of $SU(2)_I$. The new neutral gauge bosons from models ψ, χ, η, and I are the ones most frequently discussed in the literature as being representative of those which can arise in low-energy superstring-inspired E_6 models.

(ii) The left-right-symmetric model (LRM) extends [17] the SM gauge group to $SU(2)_L \times SU(2)_R \times U(1)$. The Z_2 couples to

$$\frac{1}{\sqrt{\kappa - (1+\kappa)x_W}} [x_W T_{3L} + \kappa(1-x_W)T_{3R} - x_W Q] , \tag{2.10}$$

with $\frac{1}{2} \lesssim \kappa^2 \equiv (g_R/g_L)^2 \le 1$, $T_{3L(R)}$ is the isospin assignment of the fermions under $SU(2)_{L(R)}$, and Q is the fermion electric charge. $\kappa = 1$ is assumed in our analysis below. Note that the T_{3L} assignments are the same as in the SM, while the values of T_{3R} for $u_R(d_R, e_R, \nu_R) = \frac{1}{2}(-\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, \frac{1}{2})$ and are zero for left-handed doublets, e.g., $T_{3R}(u_L) = 0$.

(iii) The alternative left-right-symmetric model (ALRM) originates [18] from E_6 GUT's and is also based on the electroweak gauge group $SU(2)_L \times SU(2)_R \times U(1)$. Since a single generation in E_6 theories contains 27 2-component fermions [in contrast with the 16 fermions per generation in SO(10)], ambiguities in quantum number assignments for even the SM fermions can arise. Here, the assignments for $(T_{3L(R)})$ differ from that of the usual LRM for $\nu_{L,R}$, e_L, and d_R. One finds that $T_{3L(R)}(\nu_L) = \frac{1}{2}(-\frac{1}{2})$, $T_{3L(R)}(e_L) = -\frac{1}{2}(-\frac{1}{2})$, and $T_{3L(R)}(d_R, \nu_R) = 0$ in the ALRM. The LRM and ALRM have identical u-quark couplings, while those for e_R and d_L remain unaltered from their SM values.

(iv) The "sequential" standard model (SSM) contains a Z_2 which is just a heavy version of the SM Z_1 boson with identical couplings.

(v) The unified model of Georgi, Jenkins, and Simmons [19] (GJS) is based on the gauge group $SU(2)_l \times SU(2)_q \times U(1)_Y$, i.e., left-handed leptons (quarks) transform as doublets under $SU(2)_{l(q)}$ and singlets under $SU(2)_{q(l)}$, and right-handed fields are singlets under both groups. The Z_2 fermionic coupling takes the form

$$c_W \left[\frac{T_{3q}}{\tan\phi} - \tan\phi\, T_{3l} \right] , \tag{2.11}$$

where $T_{3q(l)}$ is the $SU(2)_{q(l)}$ third component of isospin, $c_W = \cos\theta_W$, and ϕ is a mixing parameter which lies in the range $0.22 \lesssim s_\phi \equiv \sin\phi \lesssim 0.99$ (due to the demand that perturbation theory remain valid). Note that the extra Z current is purely left handed in this case.

(vi) The Z_2 in the Foot-Hernandez (FH) model [20] originates from an extended color group, i.e., at a large scale the gauge group is $G \equiv SU(5)_c \times SU(2)_L \times U(1)_{Y'}$, where $Y' \ne Y_{SM}$. When G breaks to the SM plus an additional unbroken SU(2) factor, a mass is generated for an additional neutral gauge boson with flavor- and color-diagonal couplings. Since most of the Z_2 arises from the $SU(5)_c \to SU(3)_c$ breaking, this Z_2 couples predominantly to $q\bar{q}$ with a strength set by g_s; the corresponding leptonic couplings are smaller by a factor of $\alpha/\alpha_s \simeq \frac{1}{15}$. Since we are only interested in the l^+l^- signature from Z_2 production, the FH Z_2 will be difficult to study via this mode at a hadron collider as the cross section for $pp \to Z_2(\mathrm{FH}) \to l^+l^-$ is quite small. As we will see below, this is reflected in a low discovery limit. The Z_2 in this model is thus qualitatively different from those in models (i)–(v) above.

(vii) In the Bagneid-Kuo-Nakagawa (BKN) model [21], a Z_2 is predicted to exist which couples differently to the third generation than to the first two generations and the model is based on the gauge group $Sp(6)_L \times U(1)_Y$. Universality requirements and the partial Glashow-Iliopoulos-Maiani (GIM) mechanism in the model allow the Z_2 mass to be $\gtrsim 1$ TeV. Although a comparison of the cross sections for $\tau^+\tau^-$ and e^+e^- final states in the vicinity of the Z_2 mass would clearly show explicit universality violation, the detection of the $\tau^+\tau^-$ final state at the SSC is made difficult by the large irreducible background from, e.g., t and W decays [12]. Here, we will ask if this Z_2 can be identified by using *only* the e^+e^- (and $\mu^+\mu^-$) final state(s) which are cleanly measurable.

(viii) As an example of a new gauge boson which may arise in, e.g., a composite model [22] of gauge bosons, we consider a Z_2 which couples only to the third component of weak isospin, T_{3L}. This Z_2 (ISO) could be an excitation of the usual SM Z_1 and we assume its overall coupling strength is the same as that of the usual Z_1.

(ix) As a last possibility, we consider a new Z boson that couples to the usual weak hypercharge (HYP), which can also occur in composite gauge-boson models [22] and more explicitly in the model of Mahanthappa and Mohapatra [23]. The coupling is normalized in the same way as the $U(1)_Y$ gauge boson of the SM.

To calculate the explicit couplings and widths of the new Z bosons in any of the above models, we normalize the g_i in Eq. (2.3) so that a common overall factor appears which is identical to that of the SM Z_1, i.e.,

$$g_i \equiv \sqrt{\rho}(\sqrt{2}G_F M_Z^2)^{1/2} . \tag{2.12}$$

This ensures that the $(g_i/e)^2$ in Eq. (2.2) is model independent:

$$\left[\frac{g_i}{e}\right]^2 = \frac{\rho G_F M_Z^2}{2\sqrt{2}\pi\alpha(M_Z)} . \tag{2.13}$$

The parameter ρ allows for the inclusion of oblique electroweak corrections and, in principle, part of the corrections to the $Z_{1,2}$ couplings due to Z-Z' mixing. In the limit $\rho \to 1$, $g_i = g/2c_W$, which is the conventional SM Z_1

coupling normalization. In our analysis, we make the simplifying assumption that Z-Z' mixing can be ignored since there is little evidence from LEP data [3] that such mixing is at all sizable. In this case, ρ is determined [1] (as is $x_W \equiv \sin^2\theta_W$) by fixing $M_Z = M_1 = 91.174$ GeV [10] as well as taking as additional input the representative values $m_t = 150$ GeV and $m_H = 100$ GeV. We thus obtain $x_W \simeq 0.2258$ and $\rho \simeq 1.006$. We note that our results are generally not very sensitive to these particular choices of the input parameters.

The Z_2 partial width for the decay $Z_2 \to \bar{f}f$ is then given by

$$\Gamma(Z_2 \to \bar{f}f) = \rho \frac{G_F M_1^2}{6\sqrt{2}\pi} M_2 N_c \beta_f \times \left[v_{2f}^2 \left[\frac{3-\beta_f^2}{2} \right] + a_{2f}^2 \beta_f^2 \right] \times \left[1 + \frac{3\alpha}{4\pi} Q_f^2 \right] F_{\mathrm{QCD}} , \tag{2.14}$$

where $\beta_f^2 \equiv 1 - 4m_f^2/M_2^2$, Q_f is the electric charge of f, and $N_c = 1(3)$ is the usual color factor for leptons (quarks). In practice, we take $m_f = 0$ except for $f = t$, where we use $m_t = 150$ GeV as stated above. The factor containing Q_f^2 accounts for one-loop pure QED corrections to the Z_2 partial width and includes a summation over both $\bar{f}f$ and $\bar{f}f\gamma$ final states. The QCD factor F_{QCD} accounts for similar strong-interaction corrections in the case where f is a quark and is given by [24]

$$F_{\mathrm{QCD}} = 1 + \frac{\alpha_s(M_2)}{\pi} + 1.409\,23 \left[\frac{\alpha_s(M_2)}{\pi} \right]^2 - 12.767 \left[\frac{\alpha_s(M_2)}{\pi} \right]^3 \tag{2.15}$$

to three-loop order in the modified minimal-subtraction ($\overline{\mathrm{MS}}$) scheme. To calculate $\alpha_s(M_2)$, we input $\alpha_s(M_1) = 0.120$ as measured at LEP [10], and run α_s up to the scale M_2 using the two-loop renormalization-group equation (RGE). To obtain the full Z_2 width, we sum the partial widths over the three generations of fermions known to exist in the SM. In particular, we ignore any possible contributions to Γ_2 arising from the existence of any new particles, and only consider the contributions of the SM fermions. We also neglect Z-Z' mixing in our calculations below, as it constrained to be tiny from measurements at LEP as discussed above [3].

III. PROCEDURE AND NUMERICAL RESULTS

Our procedure is best demonstrated by way of example. Suppose that a new Z boson from the LRM is discovered at the SSC with a mass M_2. *A priori*, we of course do not know which model gives rise to this new Z boson. As there are no real data yet, we must first duplicate this process and generate a set of Z_2 data for the LRM. Combining the formalism discussed in the preceding section with a particular set of structure functions and a knowledge of the properties of the SDC detector, we calculate (in the LRM) the expected number of events in the invariant-mass region $M_2 - \Gamma_2 \le M \le M_2 + \Gamma_2$, the Z_2 width, the forward-backward asymmetry, as well as the statistical and systematic errors associated with each of these quantities as would be obtained by the SDC. This now represents a set of artificial experimental "data." Next, we calculate the same set of quantities within the context of a second model, the ER5M for example, allowing for theoretical uncertainties due to structure functions. (Here, we follow the usual procedure and compute the quantities of interest using several different sets of parton distributions and find the resulting spread of values.) The "data" with their associated errors are then compared to the theoretical expectations for the second model (here, the ER5M) by means of a χ^2 procedure. Clearly, if M_2 is relatively small, there will be enough statistical power available to determine unmistakably that the observed Z_2 does not originate from the ER5M. However, as the value of M_2 increases, so do the statistical errors, and the LRM and ER5M become difficult to differentiate. We define the ID limit in this case to be the value of M_2 *below which* the LRM Z_2 is distinguishable from that of the ER5M at the 95% C.L. For Z_2 masses *beyond* this critical value, the models are indistinguishable at this level of confidence.

Before discussing specific results, we must address several issues. First, we need to know the new-gauge-boson discovery capabilities of the SDC/SSC. Clearly, for each extended model, the ID limit cannot be greater than the discovery reach. In order to safely say that a Z_2 has been found, we demand that at least 10 signal events are observed in the above regions of invariant mass and rapidity, with less than one background event for a single lepton channel (which we take to be electrons). This corresponds to a better than 5σ signal. To calculate this search limit, we use the next-to-leading order Diemoz-Ferroni-Longo-Martinelli (DFLM) structure functions [25] (with $\Lambda_{\overline{\mathrm{MS}}} = 200$ MeV), the central value of ϵ_l as used by the SDC [12] (i.e., $\sqrt{\epsilon_l} = 0.85 \pm 0.04$), and our knowledge of the SM and extended model couplings. Our results are shown in Table I and Fig. 1 for the various models discussed above for integrated luminosities of 10^4 and 10^5 pb^{-1}. They are qualitatively similar to those obtained in earlier analyses [7]. As we see from both the table and Fig. 1, the discovery capability of the SSC for new neutral gauge bosons is highly model dependent and ranges from less than ~ 3 TeV for the FH model to ~ 7.5 TeV for the HYP model if $\mathcal{L} = 10^4$ pb^{-1}. These results are not only important for their own sake, but also set an upper bound on the possible ID limit, e.g., a Z_2 originating from the ER5M cannot be discovered and hence cannot be identified at the SSC if its mass exceeds $\simeq 5.9$ TeV (for $\mathcal{L} = 10^4$ pb^{-1}). We also note that the discovery reach is not particularly sensitive to our choice of structure functions.

A second issue is the set of values we take for the parameters of the SDC and for the statistical and systematic errors mentioned above. In using the number of events (N) in the ranges $M_2 - \Gamma_2 \le M \le M_2 + \Gamma_2$ and $-Y \le y \le Y$ to experimentally determine the total cross section σ

TABLE I. Z_2 discovery limits in TeV (10 events) for several extended electroweak models described in the text, assuming integrated luminosities of 10^4 pb^{-1} and 10^5 pb^{-1}.

Model	10^4	10^5
ψ	5.10	7.95
χ	5.90	8.95
η	5.25	8.20
I	5.65	8.60
LRM	6.10	9.20
ALRM	6.95	10.15
SSM	6.60	9.85
FH	2.95	5.30
GJS (0.3)	5.35	8.40
GJS (0.5)	6.20	9.40
GJS (0.7)	7.20	10.45
GJS (0.9)	6.95	10.05
BKN	5.55	8.55
ISO	7.20	10.40
HYP	7.50	10.75

[defined via Eqs. (2.1) and (2.5)], we must account, not only for the statistical error, $\delta N_{\rm stat}=\sqrt{N}$, but also for the systematic errors in the luminosity ($\mathcal{L}$) and the efficiency ϵ_I. We obtain

$$\left[\frac{\delta\sigma}{\sigma}\right]_{\rm expt}=\frac{1}{\sqrt{N}}\oplus\frac{\delta\mathcal{L}}{\mathcal{L}}\oplus\frac{\delta\epsilon_I}{\epsilon_I}\ , \tag{3.1}$$

where $\oplus$ signifies that the errors are to be added in quadrature. (In practice, we also include corrections to the value of $\delta N_{\rm stat}$ due to Poisson statistics for small values of N.) As mentioned above, the SDC analysis uses the value $\sqrt{\epsilon_I}=0.85\pm0.04$ and we take $\delta\mathcal{L}/\mathcal{L}=0.07$ from present experience with the Tevatron [26] (although the latter may be reduced to 0.03 [27] at the SSC). For comparison purposes, we must also include the theoretical error, $(\delta\sigma/\sigma)_{\rm th}$, due to parton distribution uncertainties. Taking the DFLM distributions discussed above as our default, we compare the calculated values of the cross section for other DFLM sets as well as those from Harriman, Martin, Roberts, and Stirling (HMRS E and HMRS B) [28], Morfin and Tung (MT) [29], Duke and Owens (DO) [30], and Eichten, Hinchliffe, Lane, and Quigg (EHLQ) [31]. If we restrict ourselves to next-to-leading-order fits, we find that $(\delta\sigma/\sigma)_{\rm SF}\simeq0.10$ for $M_2=4$ TeV with somewhat larger (smaller) values being found for smaller (larger) values of M_2. This is as might be expected based on the analysis of Plothow-Besch [32]. For simplicity, we treat $(\delta\sigma/\sigma)_{\rm SF}$ as a constant, independent of M_2 (with a value of 0.1), since substantial improvement in the knowledge of structure functions from HERA is expected [33] in the near future. In comparing "data" with theory we include this additional error to $(\delta\sigma/\sigma)_{\rm expt}$ above, i.e.,

$$\frac{\delta\sigma}{\sigma}=\left[\frac{\delta\sigma}{\sigma}\right]_{\rm expt}\oplus\left[\frac{\delta\sigma}{\sigma}\right]_{\rm SF}\ . \tag{3.2}$$

For the statistical uncertainty in the Z_2 width, we take the value

$$(\delta\Gamma_2)_{\rm stat}=7\ {\rm GeV}\left[\frac{1000}{N}\right]^{1/2}\ , \tag{3.3}$$

as suggested by the SDC analysis [12]. We must also smear the dilepton resonance structure with the detector mass resolution (δM). Given the fine grain structure of the SDC electromagnetic calorimeter [12], δM is dominated by the energy resolution so that [12]

$$\frac{\delta M}{M}=\frac{2(0.15)^2}{M}\oplus0.01\ . \tag{3.4}$$

Hence, the "effective" measured width is $\delta\Gamma_2=(\delta\Gamma_2)_{\rm stat}\oplus\delta M$. Note that the theoretical width is also smeared by the same resolution factor δM.

Since $A_{\rm FB}$ is essentially measured by counting the number of events in the forward (N_F) and backward (N_B) hemispheres of the detector, a major contribution to the error in this quantity is statistical, i.e.,

$$(\delta A_{\rm FB})_{\rm stat}=\left[\frac{1-A_{\rm FB}^2}{N_+}\right]^{1/2}\ . \tag{3.5}$$

$N_+=N_F+N_B=\mathcal{L}\sigma^+$, where $\mathcal{L}$ is the integrated luminosity and σ^+ is defined in the preceding section. In calculating σ^+, we take $\epsilon_A=0.96$ as the efficiency for the correct measurement of the sign of the lepton's charge; this value is given in the SDC analysis [12]. The largest theoretical error arises from the parton distributions. As in the case of σ, we find that $(\delta A_{\rm FB}/A_{\rm FB})_{\rm SF}\simeq0.10$ for $M_2=4$ TeV due to these uncertainties with somewhat smaller (larger) values pertaining to the case of larger (smaller) values of M_2. As above, we assume that $(\delta A_{\rm FB})_{\rm SF}$ is a model and M_2 independent constant, i.e., $(\delta A_{\rm FB})_{\rm SF}=0.1A_{\rm FB}$. We then take

$$\delta A_{\rm FB}=(\delta A_{\rm FB})_{\rm stat}\oplus(\delta A_{\rm FB})_{\rm SF}\ , \tag{3.6}$$

in what follows, since the leading errors due to uncertainties in luminosity, lepton identification, and efficiency cancel in the ratio given in Eq. (2.8), but are included in the statistics.

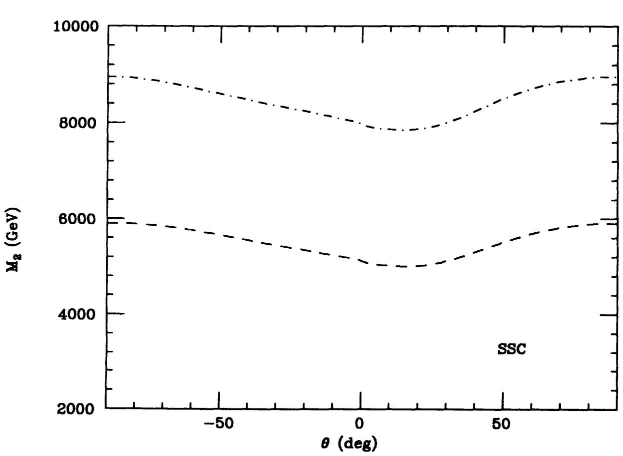

FIG. 1. Search limits for the Z_2 in the ER5M as a function of the parameter θ with an integrated luminosity of 10^4 pb^{-1} (dashed) and 10^5 pb^{-1} (dashed-dot).

Now that the values of the various input parameters as well as the errors are known, we proceed with the analysis. Following the above example, we generate a set of Z_2 "data" (with associated errors) for the LRM for a given value of M_2. The corresponding theoretical expectations for these same quantities are then calculated for a Z_2 from the ER5M with the same value of M_2 (including the theoretical uncertainties). The two sets of quantities are then compared via a χ^2 analysis. (Note that for a given model, M_2 is the only independent parameter since we hold any variable model parameters fixed when performing our χ^2 analysis.) We next raise M_2, starting from a low value, in small steps of 50 MeV until the 95% C.L. is reached and the ID limit is obtained.

Figures 2(a) and 2(b) show the results of this first example, where the produced Z_2 (i.e., the "data") actually originates from the LRM and we are testing the hypothesis where the Z_2 arises from the ER5M, for $\mathcal{L}=10^4$ and 10^5 pb^{-1}, respectively. Here the ID limit is exhibited as a function of the ER5M parameter θ. In order to demonstrate how σ, Γ_2, and A_{FB} each contribute to obtaining the ID limit, we show the ID limit obtained from σ data alone (corresponding to the dotted curve), a combination of σ and Γ_2 (dashed curve), a second combination of σ and A_{FB} (dashed-dot curve), and lastly all data (solid curve). One sees, in this particular case, that a measurement of σ alone yields a reasonable ID reach only when $|\theta| \lesssim 30°-40°$ and that no identification is possible for $|\theta| \gtrsim 50°$ unless Γ_2 and A_{FB} are also measured.

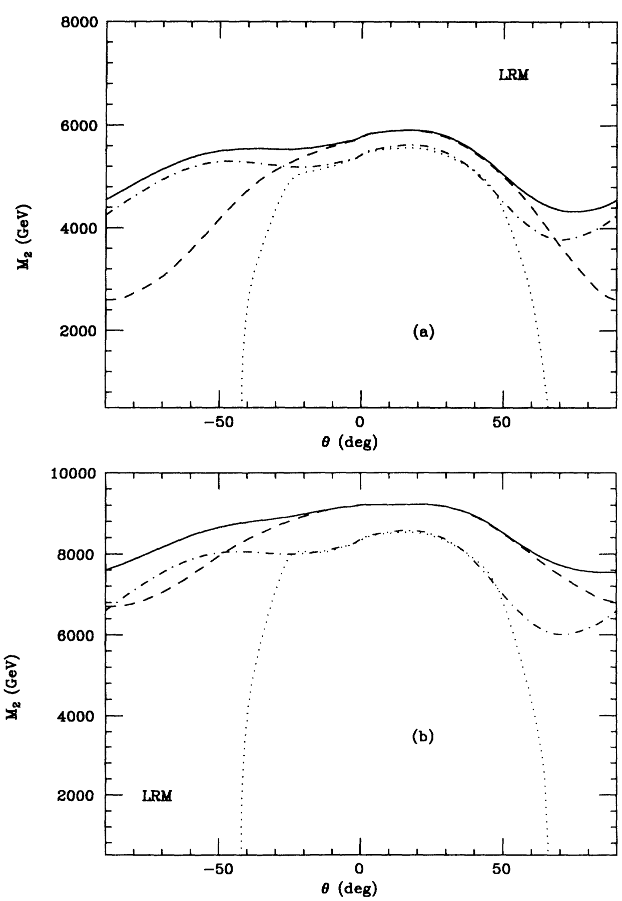

FIG. 2. ID limit at the 95% C.L. for a Z_2 originating from the LRM vs a possible Z_2 from the ER5M assuming (a) $\mathcal{L}=10^4$ pb^{-1}, or (b) $\mathcal{L}=10^5$ pb^{-1}. The dotted (dashed, dashed-dot, and solid) curves represent results from the measurements of σ alone (σ and Γ_2, σ and A_{FB}, and all data combined).

An additional, but somewhat more subtle, constraint on the ID limit shows itself in Fig. 2(b) where a flat region in the limit is obtained from the full data set in the region $\theta \simeq 0°-25°$. Since it is clear that the Z_2 must be discovered before it can be identified, the ID reach must be smaller than or equal to the discovery limit. This flat area then corresponds to a region of parameter space where the ID limit is numerically identical to the discovery limit ($=9.2$ TeV for a LRM Z_2). This is a relatively common occurrence as we will see below. This occurs in some models where the coupling strengths are large enough that the mere observation of the second Z is sufficient to distinguish it from another model with smaller couplings.

Now we turn to the comparison of other models. First, we test the ER5M against *itself*. For example, suppose that a Z_2 from the ER5M ψ (i.e., $\theta=0°$) is produced at the SSC; can this Z_2 be distinguished from another Z_2 with a *different* value of θ? Figures 3(a) and 4(a) display the results for this case with an integrated luminosity of 10^4 and 10^5 pb^{-1}, respectively. We see that for $|\theta| \gtrsim 60°$ the ID limit is again comparable to the discovery limit, and as θ nears 0° it becomes more and more difficult to isolate the observed model ψ Z_2 from another Z_2 with, e.g., $\theta=\pm 10°$. Thus, we can distinguish the observed Z_2 (with $\theta=0°$) from a Z_2 with $\theta=-10°$ only as long as $M_2 \lesssim 1.2$ TeV and all data are combined. Note that in the case of model ψ, most of the weight for setting the ID limit arises from σ and A_{FB} measurements and not from the width. The reason for this is that the new Z bosons arising from the ER5M appear to have comparable values of Γ_2 when smeared with the detector resolution. We would thus expect this result to hold for all ER5M's (i.e., all values of θ), and this is indeed observed as we will see below.

If the produced Z_2 had a different value of θ, how would our results be modified? In Figs. 3(b)–3(d) and 4(b)–4(d) we present the corresponding results assuming the observed Z_2 originates from model χ ($\theta=-90°$), η ($\theta \simeq 37.76°$), or I ($\theta \simeq -52.24°$) for an integrated luminosity of 10^4 and 10^5 pb^{-1}, respectively. For example, assuming that a 4 TeV Z_2 from model χ is produced at the SSC, we can tell with $\mathcal{L}=10^4$ (10^5) pb^{-1} that it is *not* a Z_2 with θ in the range $-30° \lesssim \theta \lesssim 60°$ ($-75° \lesssim \theta \lesssim 75°$). However, for values of θ closer to $\pm 90°$ the model χ Z_2 can no longer be distinguished at $M_2=4$ TeV. As expected, in all cases, σ and A_{FB} are the major contributors to the setting of the ID limit. In the case of model η, even for high luminosities, we see that it is quite difficult to differentiate a produced Z_2 from this model from a hypothetical Z_2 with θ in the range $-10° \lesssim \theta \lesssim 40°$. In all cases, it is clear that reasonably strong ID limits are obtainable for θ values sufficiently far away from those corresponding to the produced Z_2.

Figures 5(a)–5(d) show the ID limit at the SSC with

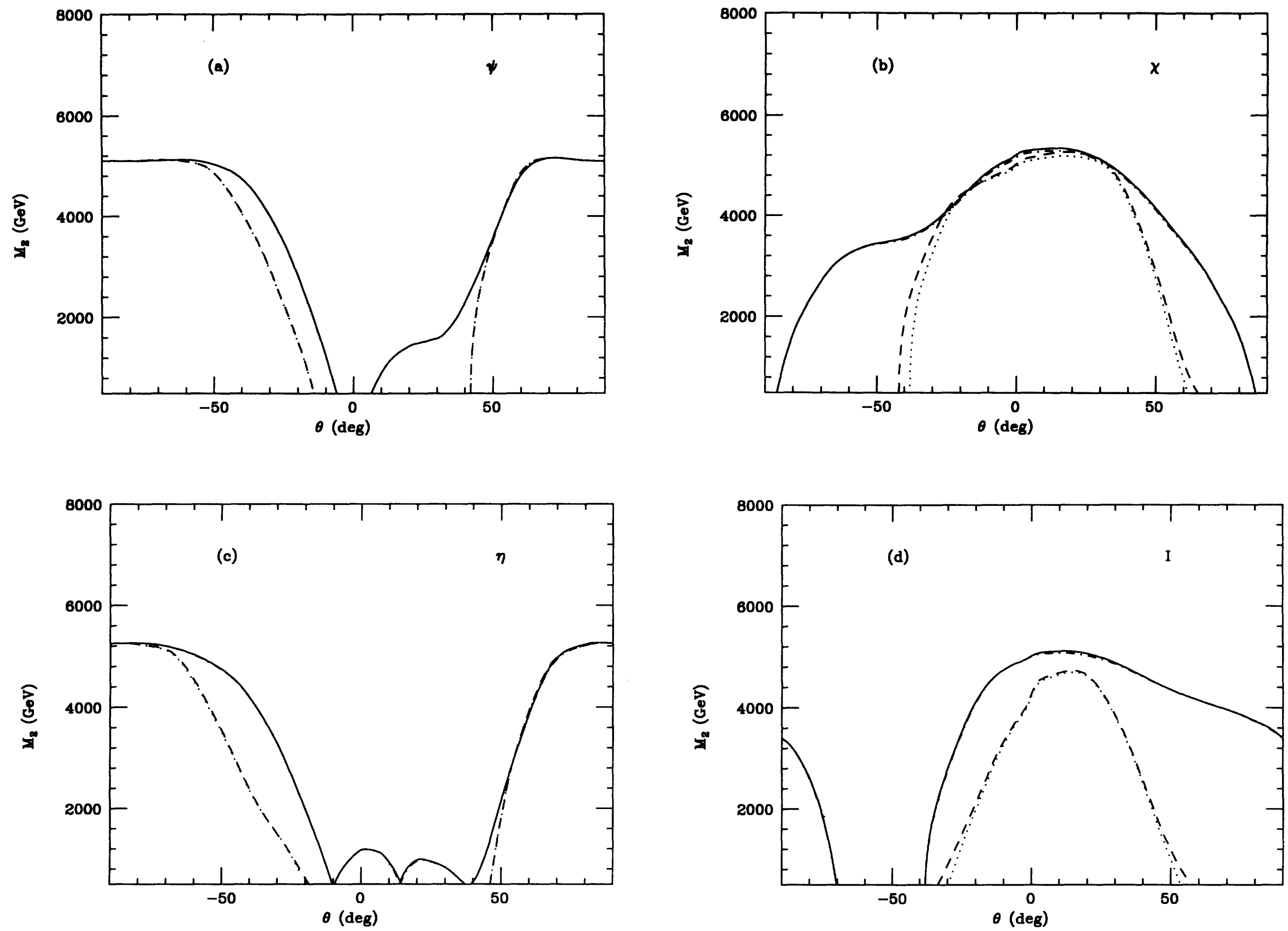

FIG. 3. 95% C.L. ID limit for a Z_2 originating from the E_6 models (a) ψ, (b) χ, (c) η, and (d) I versus a possible Z_2 from the ER5M with $\mathcal{L}=10^4$ pb^{-1}. The labeling of the curves is as in Fig. 2.

$\mathcal{L}=10^4$ pb^{-1} for the SSM, the ALRM, the GJS model with $s_\phi=0.5$, and the BKN model, assuming that these models give rise to the produced Z_2 and are contrasted to the theoretical expectations of the ER5M. Both the SSM and ALRM have ID limits which are dominated by the discovery reach; e.g., if we see a 6.2 TeV Z_2 of the SSM type, we know it cannot be a Z_2 from the ER5M at the 95% C.L. for all values of θ. In the ALRM case, we note that the cross section data alone are almost sufficient to set the entire ID limit, while in the GJS or BKN model cases, σ measurements alone result in rather poor Z_2 identification. However, for the latter two models, as soon as we add data on either A_{FB} or Γ_2, the ID limit becomes essentially identical to the discovery limit.

Table II presents ID limits for the cases not shown in the figures using the full data set (σ, Γ_2, and A_{FB}) with

TABLE II. ID limits in TeV (at the 95% C.L.) with $\mathcal{L}=10^4$ pb^{-1} for various extended models. The left-hand column lists the Z_2 models which are assumed to represent the data, while the other columns label the comparison models. In the GJS model case, the number in the parentheses is the value of s_ϕ.

Z_2 "data"	LRM	ALRM	SSM	FH	GJS (0.3)	GJS (0.5)	GJS (0.7)	GJS (0.9)	BKN	ISO	HYP
I	5.25	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65
LRM		6.10	5.15	6.10	6.10	6.10	6.10	6.10	5.55	6.10	6.10
ALRM	6.45		6.25	6.95	6.95	6.95	6.95	6.95	6.95	6.95	6.70
SSM	4.80	5.90		6.60	6.60	6.60	6.40	6.10	6.30	6.45	6.60
GJS (0.7)	7.20	7.20	6.65	7.20	7.20	7.20		3.70	6.95	0.50	6.85
GJS (0.9)	6.95	6.55	6.95	6.95	6.95	6.95	3.60		6.70	3.95	6.95
ISO	7.20	7.20	6.60	7.20	7.20	7.20	4.50	4.05	7.00		6.75
HYP	7.10	6.80	7.20	7.50	7.50	7.50	7.15	7.50	7.50	7.05	

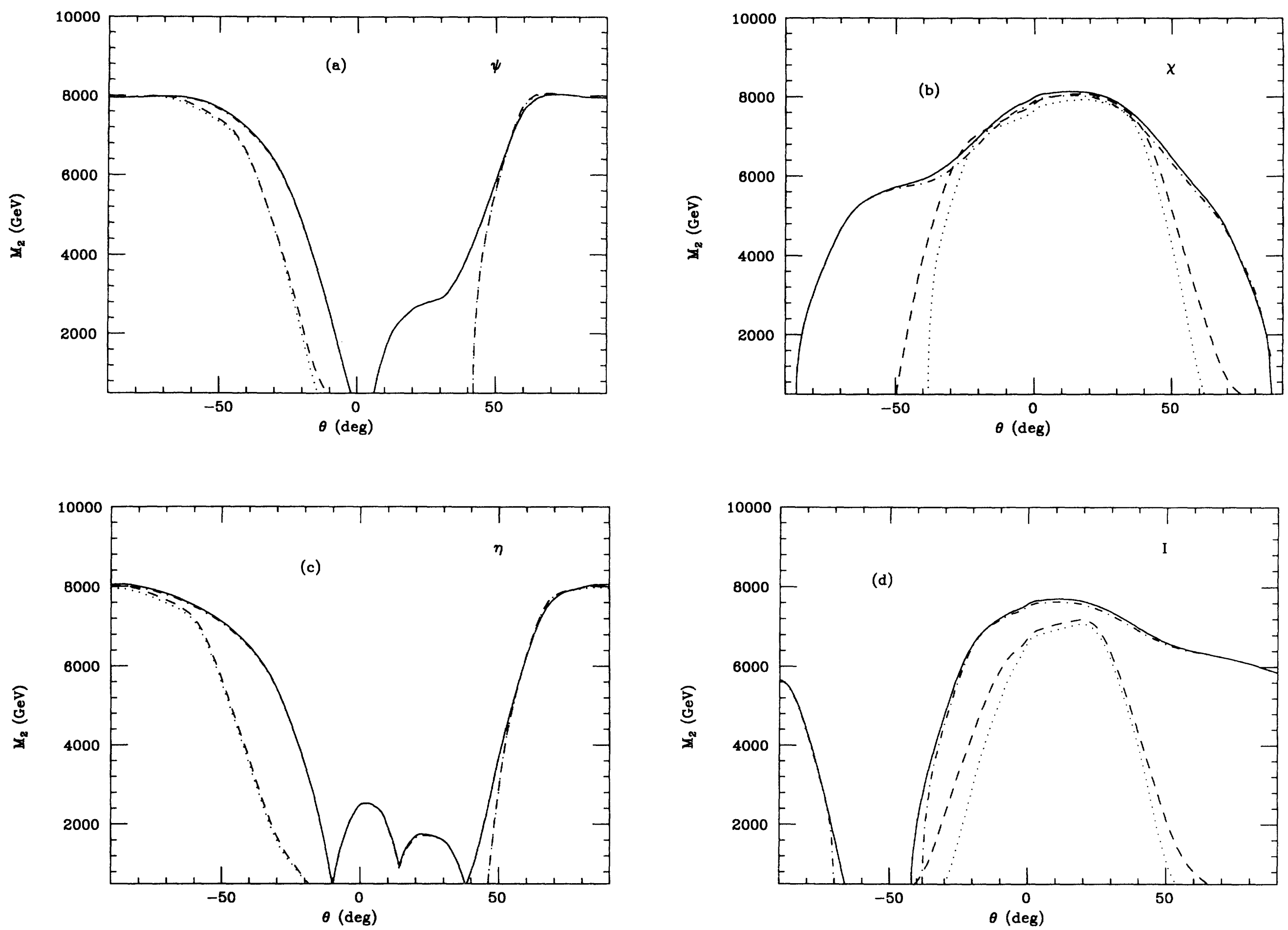

FIG. 4. Same as Fig. 3, except for $\mathcal{L}=10^5$ pb^{-1}.

$\mathcal{L}=10^4$ pb^{-1}. The models listed on the left side of the table correspond to the Z_2 which is actually produced at the SSC (i.e., the "data") and is then compared to the predictions from the models which label the columns. For example, if a Z_2 of the LRM type is produced, we see from the table that it can be differentiated from a new Z boson contained in the SSM (BKN) model for values of its mass up to 5.15 (5.55) TeV. Note that in most cases the ID limits are not too far from the discovery reach. For the E_6 models ψ, χ, and η, the FH model, the GJS model with $s_\phi=0.3$ or 0.5, and the model of BKN, the ID limits are identical to the discovery limits when they are contrasted against the other models listed in the table, and hence are not listed in the table. When $\mathcal{L}$ is increased to 10^5 pb^{-1}, the discovery reach and the ID limits become nearly identical in almost all the models, if data on σ, Γ_2, and A_{FB} are combined.

Given a fixed integrated luminosity, we now briefly explore how modifications in our assumed values for $\delta\mathcal{L}/\mathcal{L}$ and ϵ_l, the addition of data using the $\mu^+\mu^-$ final state, and a reduction in systematic errors from uncertainties in the parton distributions would change the results presented above. Figure 6(a) shows how the results for the LRM in Fig. 2(a) would be altered if $\delta\sqrt{\epsilon_l}=0.03=\delta\mathcal{L}/\mathcal{L}$ and $(\delta\sigma/\sigma)_{SF}=(\delta A_{FB}/A_{FB})_{SF}=0.05$ with only electron pair data, while Fig. 6(b) includes μ-pair data with a muon pair identification efficiency [12] of 91% of that for electrons. Note that since the μ-pair mass resolution of the SDC is relatively poor, muons are only useful in improving the statistics on σ and A_{FB}. Figure 6(a) shows that, although the ID limits from using σ *alone* improve, the combination of all possible data does not give a substantial increase from our previous results in the overall limit. If muon data are included, Fig. 6(b) demonstrates that the additional statistics show up mainly in the regions near $\theta=\pm 90°$ where the ID reach is found to increase by at most $\simeq 0.2-0.3$ TeV. We have also considered the influence of refining the lepton-pair mass resolution to $\delta M/M=0.005$ (for large values of M); this too has a relatively negligible effect (at the level of $\simeq 0.1-0.2$ TeV) on the results obtained above.

Now that we know the SDC/SSC can not only discover new gauge bosons but can also distinguish between different extended models, we now explore how well the

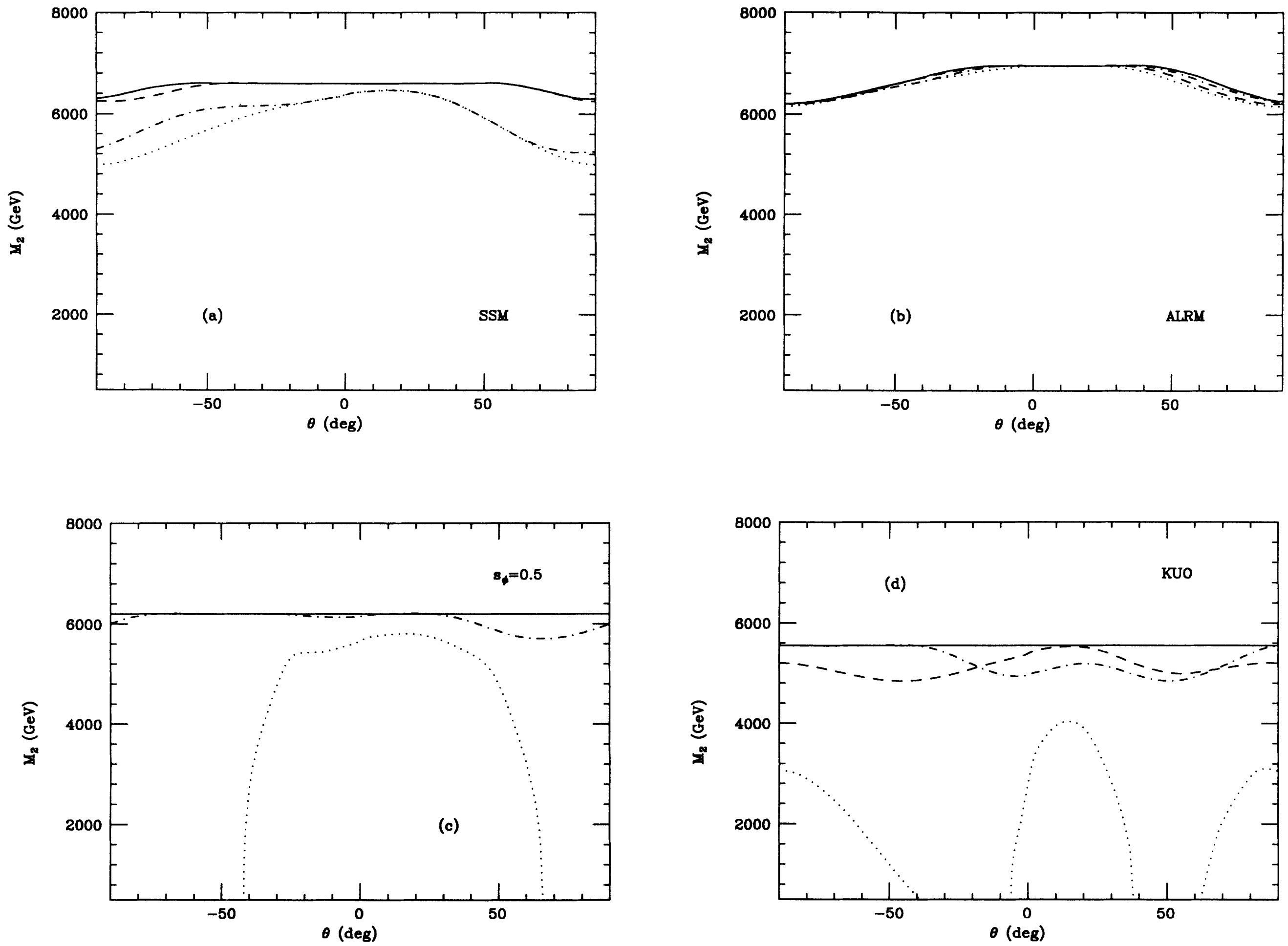

FIG. 5. ID limit at the 95% C.L. for a Z_2 arising from the (a) SSM, (b) ALRM, (c) GJS model with $s_\phi=0.5$, and (d) BKN model vs a possible Z_2 from the ER5M with $\mathcal{L}=10^4$ pb^{-1}.

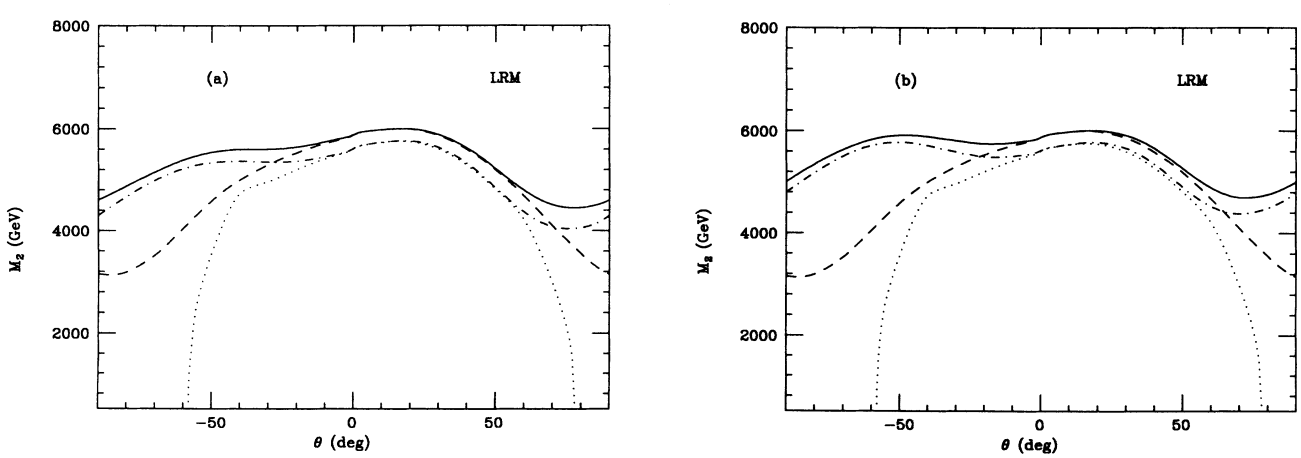

FIG. 6. Z_2 ID limit for the LRM, as in Fig. 2(a), but with the parameters $\delta\mathcal{L}/\mathcal{L}=\delta\sqrt{\epsilon_l}=0.03$, $(\delta\sigma/\sigma)_{SF}=(\delta A_{FB}/A_{FB})_{SF}=0.05$, (a) without and (b) with the contribution from muon pairs.

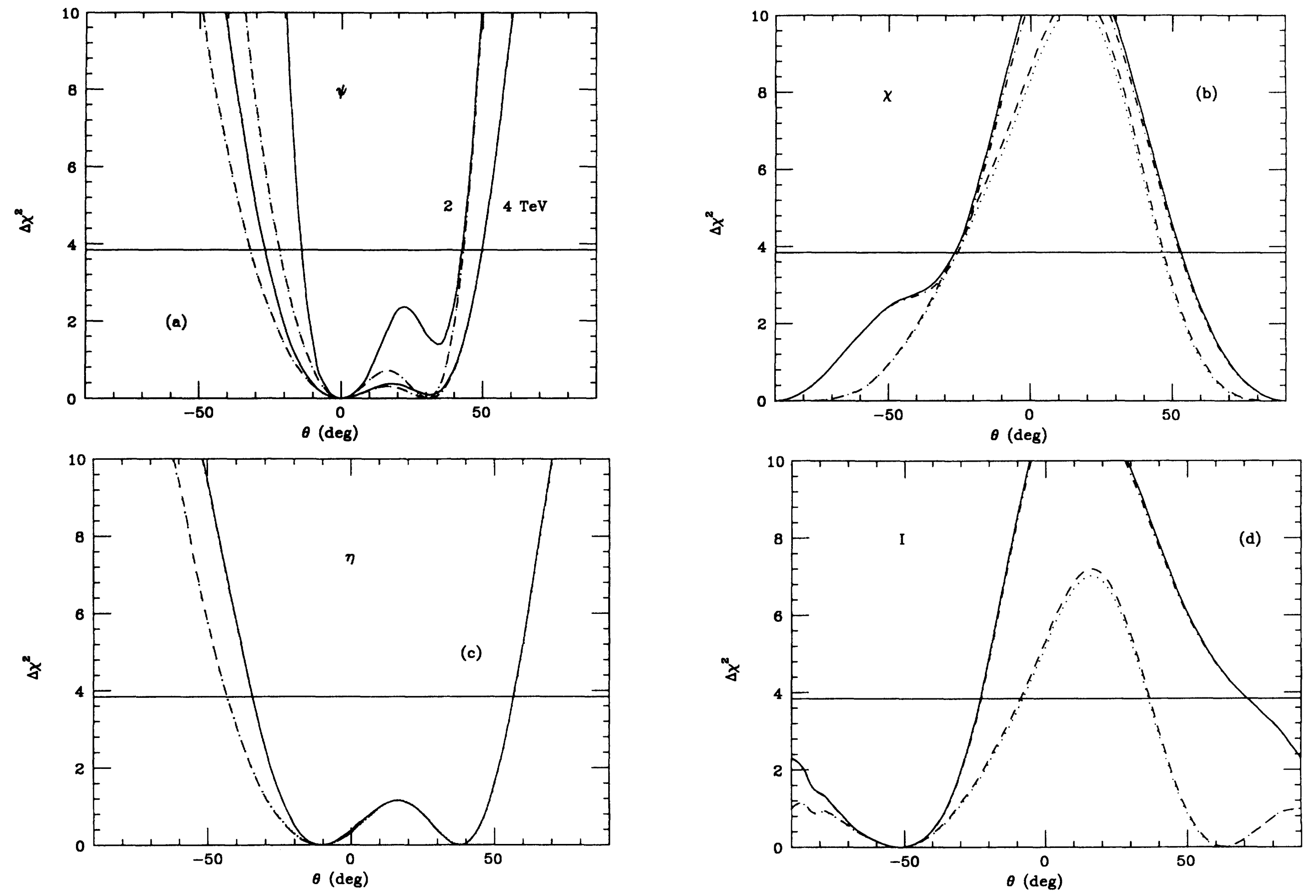

FIG. 7. $\Delta\chi^2$ as a function of θ assuming $\mathcal{L}=10^4$ pb^{-1} for (a) model ψ with $M_2=2$ TeV (and 4 TeV) corresponding to the inner (outer) set of curves. The horizontal solid line represents the 95% C.L. in determining the range of θ, the dotted (dashed, dashed-dot, and solid) curves depict the results from measurements of σ alone (σ and Γ_2, σ and $A_{\rm FB}$, and all data combined). Parts (b), (c), and (d) present comparable results for $M_2=4$ TeV in models χ, η, and I, respectively.

TABLE III. Determination of the E_6 parameter θ (at the 95% C.L.) by the SDC with $\mathcal{L}=10^4$ pb^{-1} and 10^5 pb^{-1} for $1\le M_2\le 5$ TeV for Z_2 bosons originating from models ψ, χ, η, and I.

Model	M_2 (TeV)	10^4 pb^{-1}	10^5 pb^{-1}
ψ	1	$-7°$ to $11°$	$-4°$ to $12°$
	2	$-14°$ to $43°$	$-8°$ to $14°$
	3	$-22°$ to $45°$	$-11°$ to $40°$
	4	$-26°$ to $49°$	$-13°$ to $43°$
	5	$-41°$ to $58°$	$-17°$ to $44°$
χ	1	$-95°$ to $-85°$	$-95°$ to $-85°$
	2	$-101°$ to $-79°$	$-96°$ to $-84°$
	3	$-115°$ to $-66°$	$-98°$ to $-82°$
	4	$-127°$ to $-27°$	$-104°$ to $-77°$
	5	$-143°$ to $-11°$	$-113°$ to $-67°$
η	1	$-13°$ to $46°$	$34°$ to $41°$
	2	$-19°$ to $50°$	$-10°$ to $47°$
	3	$-28°$ to $54°$	$-18°$ to $49°$
	4	$-34°$ to $57°$	$-21°$ to $50°$
	5	$-51°$ to $67°$	$-26°$ to $52°$
I	1	$-73°$ to $-39°$	$-70°$ to $-40°$
	2	$-75°$ to $-36°$	$-71°$ to $-38°$
	3	$-82°$ to $-29°$	$-74°$ to $-37°$
	4	$-108°$ to $-23°$	$-76°$ to $-35°$
	5	$-148°$ to $-7°$	$-82°$ to $-32°$

SDC/SSC can be used to determine the couplings of the Z_2. For example, can the value of θ actually be determined in the case of the ER5M? For illustration, suppose that a 2 TeV Z_2 arising from the ER5M ψ is observed at the SDC/SSC with $\mathcal{L}=10^4$ pb^{-1}. Can the data on σ, Γ_2, and $A_{\rm FB}$ be used to determine an allowed range for θ at the 95% C.L.? The analysis closely follows that for the results above, i.e., for each value of θ we perform a χ^2 analysis and in this case, we find a χ^2 minimum at $\theta=0°$ with a variation about this minimum as given in Fig. 7(a). The figure shows that the 95% C.L. limit (represented by the solid horizontal line) on the allowed range of θ is $-14°\le\theta\le 43°$ for $M_2=2$ TeV. This means that we can determine $\theta=0°{}^{+43°}_{-14°}$ from a fit to the "data;" clearly, θ is not very well determined for these values of $\mathcal{L}$ and M_2. For larger values of M_2 we experience a drastic reduction in statistics, in comparison to the 2 TeV case, and θ becomes even more poorly determined at 95% C.L., i.e., $\theta=0°{}^{+49°}_{-26°}$ for $M_2=4$ TeV. Note that as in the case of the ID reach discussed above, the dominant contributors to this bound are the cross section and forward-backward asymmetry.

The fact that θ is poorly determined for larger new Z-boson masses is a general feature of all of these models; Figs. 7(b)–7(d) show $\Delta\chi^2$ as a function of θ for models χ,

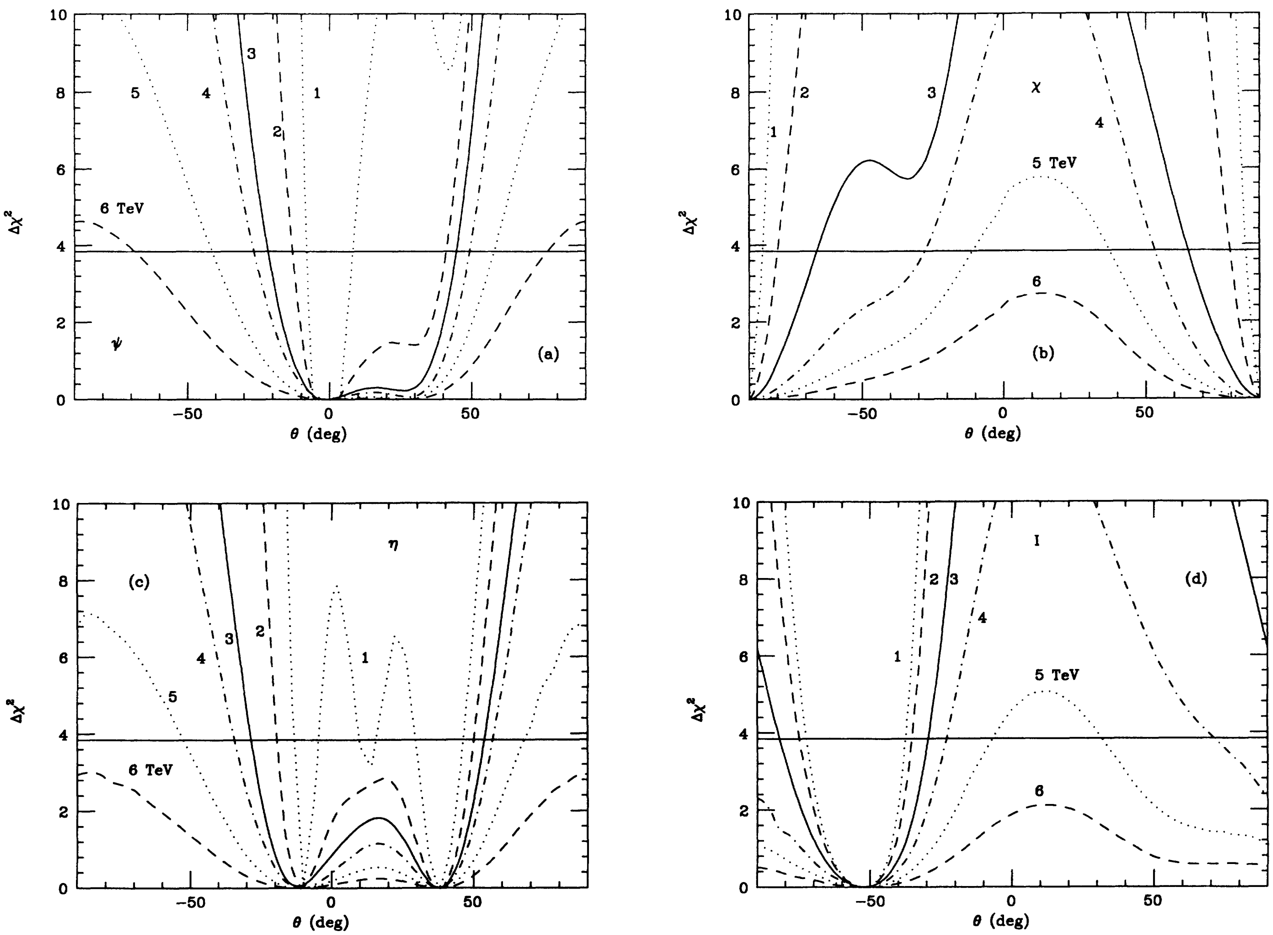

FIG. 8. $\Delta\chi^2$ as a function of θ using data on σ, Γ_2, and A_{FB} with an integrated luminosity of 10^4 pb^{-1} for several different values of M_2 in the E_6 models (a) ψ, (b) χ, (c) η, and (d) I.

η, and I with $M_2=4$ TeV. One sees in all cases that θ is not very well determined. Using the complete set of data, one sees in Figs. 8(a)–8(d) how the determination of the parameter θ deteriorates in all of these models as the value of M_2 increases. The resulting allowed ranges for θ at 95% C.L. for models ψ, χ, η, and I, assuming $1 \leq M_2 \leq 5$ TeV and either $\mathcal{L}=10^4$ or 10^5 pb^{-1}, are presented in Table III. For some models we see that even for new Z bosons as light as 1 TeV and with large integrated luminosities, θ cannot be very accurately determined at the 95% C.L. using the SDC.

What happens if we try to determine the value of θ for a Z_2 which arises from a model which is not of the ER5M type? Of course, θ cannot actually be determined by such an analysis since *no* value of θ will correspond to the couplings of the Z_2 which is actually observed by the SDC detector. Clearly, if the value of M_2 is below the ID limit for a new Z boson from the LRM (as compared to a Z_2 arising from the ER5M), the value of $\Delta\chi^2$ will be large and the new Z boson will not be misidentified. In Fig. 9 we show $\Delta\chi^2$ as a function of θ for various values of M_2 for a new Z boson originating from the LRM assuming $\mathcal{L}=10^4$ pb^{-1}. For example, with $M_2=3$ TeV, $\Delta\chi^2>10$ for all values of θ and we clearly distinguish the two models; however, if $M_2=6$ TeV, $\Delta\chi^2 \lesssim 4$ for almost all values of θ and we no longer can make any statement about the identification as compared to the class of E_6 ER5M. Figure 9 can also be used to reset the confidence

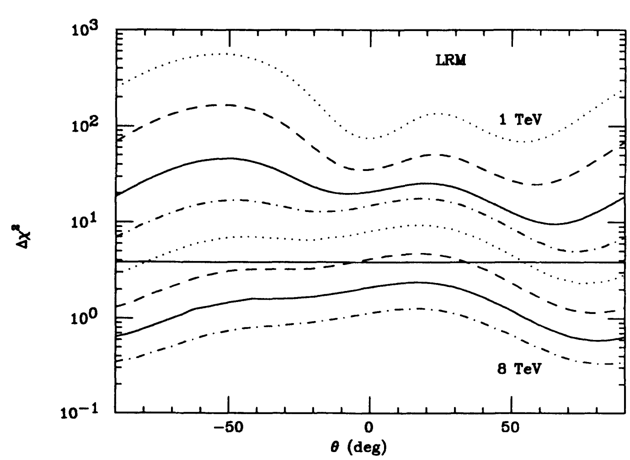

FIG. 9. Same as in Fig. 8, except for the LRM. The top dot curve is for $M_2=1$ TeV and each successive lower curve corresponds to a 1 TeV increase in M_2.

level for distinguishing between two models. If, for example, one wanted to say that the produced Z_2 was not from the ER5M at the 5σ level (corresponding to a $\Delta\chi^2$ of 25), one can tell from Fig. 9 that only new Z bosons as light as $\simeq 3.5$ TeV could be identified at this level of confidence instead of the 5–6 TeV value shown in Fig. 2(a).

IV. CONCLUSIONS

In this paper we have addressed the problem of identifying the origin and couplings of a new neutral gauge boson at the SSC with a realistic detector such as the SDC. This is made difficult by the fact that hadron colliders permit measurements of only a few quantities with which Z_2 physics can be probed and by the realities of finite detector efficiencies and resolution. We have found, however, that combined measurements of the Z_2 production cross section, width, and forward-backward asymmetries can yield significant model discrimination at the SSC up to mass scales of several TeV. In many cases, the Z_2 ID limit was found to be almost equal to the discovery reach. In contrast, the determination of the couplings of a Z_2 at the SSC is a much more difficult prospect; e.g., for new Z bosons in the ER5M with relatively small masses, we found that the bounds one can obtain on the coupling parameter θ were reasonably weak at the 95% C.L.

A comparison of the Z_2 coupling determination and identification abilities of the LHC, SSC, and a high energy linear e^+e^- collider will be addressed in a future work [34].

ACKNOWLEDGMENTS

We thank V. Barger and K. Whisnant for fruitful discussions pertaining to this work. T.G.R. thanks the Phenomenology Institute at the University of Wisconsin-Madison for its hospitality and use of its facilities. This research was supported in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation and in part by the U.S. Department of Energy under Contracts Nos. DE-AC02-76ER00881 and W-7405-Eng-82.

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