Z' SEARCHES: FROM TEVATRON TO LHC

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The CDF collaboration has set lower limits on the masses of the Z' bosons occurring in a range of E_6 GUT based models. We revisit their analysis and extend it to certain other E_6 scenarios as well as to some general classes of models satisfying the anomaly cancellation conditions, which are not included in the CDF analysis. We also suggest a Bayesian statistical method for finding exclusion limits on the Z' mass, which allows one to explore a wide range of the $U(1)'$ gauge coupling parameter. This method also takes into account the effects of interference between the Z' and the SM gauge bosons.

1 Introduction

A neutral Z' gauge boson appears in numerous models containing the SM gauge symmetry group along with an additional $U(1)$ symmetry (for a review, see [1]). Grand Unified Theories (GUTs) larger than the original $SU(5)$ model, such as $SO(10)$ [2] or E_6 [3,4], break down to the SM as: $E_6 \to SO(10) \times U(1)_\psi$, with in turn $SO(10) \to SU(5) \times U(1)_\chi \to \mathrm{SM} \times U(1)_\chi$ [5]. The Z' thus surviving at the electroweak (EW) scale can be written as the linear combination,

$$Z' = \cos\alpha \cos\beta Z_\chi + \sin\alpha \cos\beta Z_Y + \sin\beta Z_\psi. \quad (1)$$

If kinetic mixing [6,7,8] with the hypercharge group $U(1)_Y$ is neglected by setting $\alpha = 0$ in eq. (1), one obtains some well–known Z' bosons by adjusting β. These include Z_χ ($\beta = 0°$), Z_ψ ($\beta = 90°$), Z_η ($\beta \approx -52.2°$) [9], Z_I ($\beta \approx 37.8°$) [3], Z_S ($\beta \approx 23.3°$) [10,11] and Z_N ($\beta \approx 75.5°$) [12]. The inclusion of kinetic mixing results in certain other phenomenologically interesting cases, such as Z_{dph} ($\alpha, \beta \approx -78.5°, 37.8°$) which does not couple to the d–type quarks, Z_R ($\alpha, \beta \approx 50.8°, 0°$) [13] which couples to the right–handed fermions only and Z_{B-L} ($\alpha, \beta \approx -39.2°, 0°$) [14], where B is the baryon number and L the lepton number of an ordinary fermion. The Z_{LR} which exists in models with left–right symmetry [15] is equivalent to the linear combination: $\sqrt{3/5}\,(\bar\alpha\, Z_R - Z_{B-L}/2\bar\alpha)$, where $\bar\alpha \equiv \sqrt{g_R^2/g_L^2 \cot^2\theta_W - 1}$, with θ_W being the weak mixing angle and $g_{L,R}$ being the $SU(2)_{L,R}$ coupling strengths, respectively. The Z_{LR} studied here corresponds to the specific case of $g_L = g_R$. In addition to these E_6 based models, a Z_{string} from a specific superstring model [16] and a sequential Z_{SM} are also included in this analysis.

A number of other classes of one or more–parameter models have been discussed [17,18,1]. Without the assumption of unification at the GUT scale, but assuming nullification of anomalies using three families of exotics (which is not the case in some supersymmetric models), there are

Table 1: E_6 fermion charges, ϵ_f, in terms of z_f, their values in the corresponding x–parameter models. Also given are the angles α and β yielding these models.

	$q+xu$	$10+x\bar{5}$	$d-xu$
ϵ_f	$\frac{3}{2\sqrt{7-2x+x^2}}z_f$	$-\frac{3}{2\sqrt{4+x+x^2}}z_f$	$\frac{3}{2\sqrt{1-x+x^2}}z_f$
$\tan\beta$	0	$-\sqrt{\frac{3}{5}}(\frac{3+x}{1-x})$	$\frac{\sqrt{3}(1-x)sign(5-x)}{\sqrt{5-2x+5x^2}}$
$\tan\alpha$	$\sqrt{\frac{3}{2}}(\frac{1+x}{x-4})$	0	$2\sqrt{6}(\frac{x}{5-x})$

four 'one-parameter' models [18], with fermion charges $B-xL$, $d-xu$, $q+xu$ and $10+x\bar{5}$, with x arbitrary. The last three of these correspond to the generalized E_6 charges in eq. (1). ($q+xu$ corresponds to arbitrary superpositions of Y and $B-L$, while $10+x\bar{5}$ corresponds to the E_6 models without kinetic mixing.) We have, therefore, normalized the fermions charges, z_f, in the x–parameter models to their E_6 values, ϵ_f. These charges are given in Table 1.

2 Z' production at CDF and limits on its mass

The total cross–section for the Drell–Yan (DY) process at a hadron collider, with a neutral gauge boson B as the mediator and $\mu^+\mu^-$ as the outgoing particles, is given as [20]

$$\sigma = \frac{2}{s}\int_0^{\sqrt{s}} M dM \sigma_{diff}, \tag{2}$$

where M is the invariant mass of the muon pair, $\sqrt{s}$ is the center–of–mass (CM) energy, and

$$\sigma_{diff} = \int_{M^2/s}^{1} dx_1 \frac{1}{x_1}\sum_q \hat{\sigma}(M^2)\frac{K}{N_c}\Big\{f_q^A(x_1,M^2)f_{\bar{q}}^B(x_2,M^2) + f_{\bar{q}}^A(x_1,M^2)f_q^B(x_2,M^2)\Big\}, \tag{3}$$

where $N_c = 3$ is the quark color factor. x_1 and $x_2(\equiv \frac{M^2}{x_1 s})$ above are the momentum fractions of the ingoing partons having parton distribution functions (PDFs) $f_{q/\bar{q}}^{A/B}$ for hadrons A and B. α_s is the strong coupling constant and $K = K_C + K_E$, with K_C being the QCD K–factor and K_E being the multiplicative factor due to QED corrections. $\hat{\sigma}(M^2)$ is equal to

$$\int_{-1}^{1} d\cos\theta^* \frac{1}{128\pi M^2}\Big[\left(|A_{LL}|^2+|A_{RR}|^2\right)(1+\cos\theta^*)^2 + \left(|A_{LR}|^2+|A_{RL}|^2\right)(1-\cos\theta^*)^2\Big], \tag{4}$$

with θ^* being the polar angle defined in the CM frame and the individual amplitudes given as

$$A_{ij} = -Qe^2 + \frac{M^2}{M^2-M_Z^2+iM_Z\Gamma_Z}C_i^Z(q)C_j^Z(l) + \frac{M^2}{M^2-M_{Z'}^2+iM_{Z'}\Gamma_{Z'}}C_i^{Z'}(q)C_j^{Z'}(l), \tag{5}$$

where i,j are run over L,R. Q and e are the electric charges of the contributing quark and the muon, respectively. $C_{L,R}^{Z,Z'}(f) \equiv g_{1,2}\epsilon_{L,R}^{Z,Z'}(f)$, with $g_1 = e/\sin\theta_w\cos\theta_w$ being the gauge coupling strength of the Z boson, g_2 the Z' coupling and $\epsilon_{L,R}^{Z,Z'}$ the EW and $U(1)'$ charges of the fermion f. $\Gamma_{Z,Z'}$ are the total decay widths of the Z and Z' bosons having masses $M_{Z,Z'}$.

We first follow the CDF analysis [21] and use the LO expression given in eq. (2) to calculate the cross–section due to the Z' alone, neglecting the γ and Z contributions to the amplitudes in eq. (5). We employ LO CTEQ6L PDFs [22] and mass–dependent NNLO K_C [18] and NLO K_E [23] values, and assume that the Z' decays into SM fermions only, which are taken to be massless. We achieve up to 99.8% agreement on the 95% confidence level (C.L.) $M_{Z'}$ lower limits with

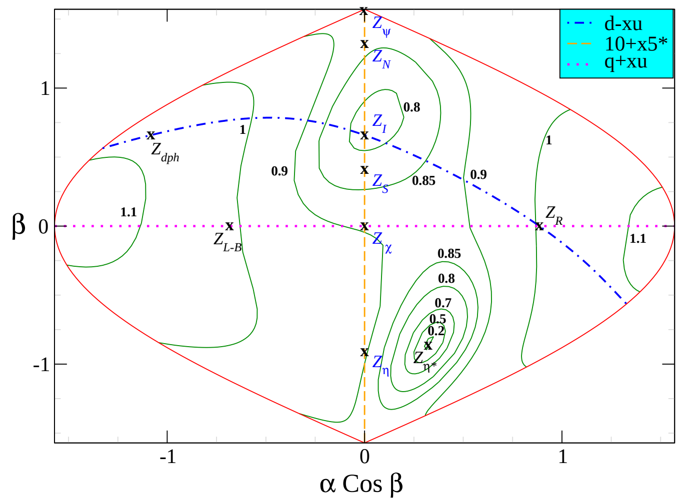

Figure 1: Contours in $M_{Z'}$ limits mentioned on/beside them. x shows the location of a particular E_6 model within a contour. The dotted, dashed and dot–dashed lines correspond to the three x–parameter models. Z_{η^*} is a leptophobic boson which will not be observable in the di–lepton channels.

Table 2: Numerical limits in GeV on the mass of the Z' boson in various models.

Z_χ	Z_ψ	Z_η	Z_N	Z_S	Z_I	Z_{B-L}	Z_R	Z_{LR}	Z_{dph}	Z_{string}	Z_{SM}
895	883	910	865	823	790	1012	1006	959	1079	710	1030

Table 3: Limits on $M_{Z'}$ in the Z_χ model from the LHC.

$\mathcal{L}$ (fb^{-1})/$\sqrt{s}$ (TeV)	3.5	7	14	28
3	1.0	1.85	3.0	4.65
30	1.5	2.5	4.1	6.7
300	2.2	3.3	5.4	9.7
3000	3.9	5.55	7.9	12.2

the CDF analysis, for the E_6 models included therein, and obtain new limits for the rest of the models. The numerical values of the limits are given in Table 2 and the α, β parametrization of the models with contours in $M_{Z'}$ is plotted in Fig. 1. In Table 3 we give limits obtained for the LHC with a similar approach for some expected integrated luminosity and CM energy values.

3 Bayesian statistical method

The CDF analysis uses signal templates generated with a fixed resonance pole width, $\Gamma = 2.8\% \times M_{Z'}$. However, there is no fundamental reason to only look for such a narrow Z'. A wide Z' resonance, implying a strongly coupling boson, could well be scattered over a few bins and no significant enhancement above the background will be visible. Besides, the effects of interference between the various bosonic contributions to the propagator, i.e., between γ, Z and Z' (see eq. (5)), are lost in their approach. These effects could in principle cause a considerable enhancement or dip in the number of events in several accompanying low M^{-1} bins, e.g., in the case of a strongly interacting Z' boson with mass just beyond the kinematic reach of the CDF. Finally, the CDF limits assume a fixed GUT–based g_2 and it is not straightforward to extend the limits to other g_2 values, particularly in the strong coupling regime (see, however [24]).

Therefore, we propose a Bayesian statistical method which allows one to vary g_2 in order to obtain the corresponding limit on $M_{Z'}$. It is based on the likelihood function Ł, written as

$$Ł(\vec{\mu}|\vec{n}) = \Pi_i^B P(n_i|\mu_i), \tag{6}$$

where P is the Poisson probability of finding n_i events given μ_i expected events in the ith bin with B total bins. Ł in eq. (6) is then evaluated using two hypotheses: the null hypothesis, $Ł(\vec{\mu^b}|\vec{n})$, assumes that the DY process occurs only via γ and Z, and the signal hypothesis, $Ł(\vec{\mu^t}|\vec{n})$, with $\vec{\mu^t} = \vec{\mu^b} + \vec{\mu'}$, wherein the Z' boson also contributes to the cross–section along with the SM gauge bosons. The SM events, μ^b, expected in an invariant mass bin are calculated as

$$\mu^b = \mathcal{L}\sigma_{SM} = \frac{2E\mathcal{L}}{s}\int_{bin} A dM_p^{-1}\int_0^{\sqrt{s}} M dM \mathbf{p}(M_p^{-1}|M^{-1})\sigma_{diff} + n_{\rm BG}, \tag{7}$$

where $\mathcal{L} = 2.3$ fb^{-1} is the integrated luminosity at the CDF, $E = 0.982$ is the detector *efficiency* and A is the CDF *acceptance*, which is a mass–dependent multiplicative factor. M_p in the above equation is the muon–pair mass measured by the detector, $n_{\rm BG}$ refers to the non–DY events and the probability density is given as

$$\mathbf{p}(M_p^{-1}|M^{-1}) = M_p b^a e^{-b}/\Gamma(a), \tag{8}$$

with $a = (M^{-1}/\Delta)^2$, $b = M^{-1}M_p^{-1}/\Delta^2$, where $\Delta = 0.17$ TeV^{-1} is the variance. The purpose of the above probability function is to smear over the DY background before distributing it into bins, hence accounting for the mis–identification of an event in a bin where it does not actually belong. For μ', a χ^2 function is constructed as

$$\chi^2_{\mu'} = -2LLR = -2\ln\left(\frac{Ł(\vec{\mu^t}|\vec{n})}{Ł(\vec{\mu^b}|\vec{n})}\right) = -2\sum_i^B\left(\mu_i^b - \mu_i^t + n_i\ln\left(\frac{\mu_i^t}{\mu_i^b}\right)\right), \tag{9}$$

and is minimized to obtain the best–fit values in the given range of g_2 and $M_{Z'}$, which correspond to a Z' boson with cross–section μ' best favored by the data. The contours in g_2 and $M_{Z'}$, for a certain C.L. value specified by the allowed number of standard deviations, $\Delta\chi^2$, from the minimum, can then also be drawn, giving the exclusion limits on these parameters. Our preliminary contours are given in Fig. 2 for Z_χ as a representative model. The numerical value of the 95% C.L. limit is 913 GeV for $g_2 = 0.461$, which is about 21 GeV higher than the CDF value. We next plan to undertake a global analysis including constraints from electroweak precision data[13]. Eventually, a similar statistical analysis of the LHC data, as soon as it is released, will also be performed.

Acknowledgments

The work at IF-UNAM is supported by CONACyT project 82291–F. The work of P.L. is supported by an IBM Einstein Fellowship and by NSF grant PHY–0969448.

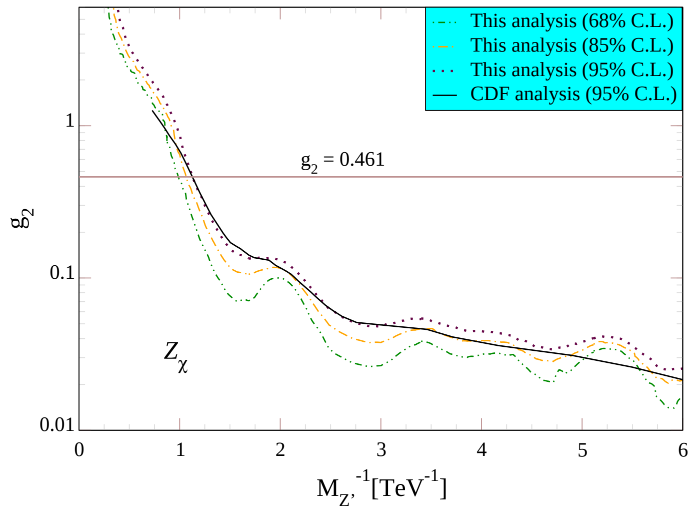

Figure 2: Exclusion contours for the Z_χ boson. The dotted, dot–dashed and double–dot–dashed curves correspond to the C.L. values given and the solid curve represents the CDF limits generalized to other g_2 values.

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