Bounds on new Z bosons

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Since new Z bosons (Z') are predicted by many approaches to particle physics beyond the standard model, the absence of a signal in lepton pairs at hadron colliders implies important, but very model-dependent, lower limits on Z' masses. We present an analytical procedure for converting an experimental limit on $\sigma(Z')B(Z'\to l^+l^-)$ into mass limits in a large set of models. Explicit results are given for present CERN and future Fermilab collider data. We include renormalization effects so that consideration can be restricted to grand-unification models.

The existence of new neutral interactions at electroweak scales is a prediction of many extensions of the standard model.[1] When the corresponding new neutral gauge bosons Z' couple to both quarks and leptons, large hadron colliders, through the lepton pair signal l^+l^-, are a window with a view to a large range of Z' masses.[2–5] In fact the absence of an excess of l^+l^- events bounds the Z' masses as well as the corresponding interactions. These bounds, as the Z' couplings themselves, are largely model dependent. In this paper we present a simple analytical expression to translate the bounds on $\sigma(Z')B(Z'\to l^+l^-)$, or equivalently on $R=\sigma(Z')B(Z'\to l^+l^-)/\sigma(Z)B(Z\to l^+l^-)$,[6] at CERN $Sp\bar{p}S$ and the Fermilab Tevatron, into bounds on the Z' mass for the different [E_6 (Ref. 8)] superstring-inspired models.[9] In the calculation we include the effects due to the renormalization of the gauge couplings from the unification scale down to M_Z.[10,11] Other popular models are analyzed for comparison.[2,12–14]

We observe that a bound on R can be translated into a bound on the Z' mass (for any given model) by means of the simple parametrization

$$M_{Z'}(R)=M_{Z'}(R_0)\left[1+c_1\log_{10}\frac{R}{R_0}+c_2\left[\log_{10}\frac{R}{R_0}\right]^2\right], \tag{1}$$

where R_0 is chosen conveniently for each collider. In particular,

$$R_0=0.025\ (0.010) \tag{2}$$

at $Sp\bar{p}S$ (Tevatron). $M_{Z'}(R_0)$, c_1, and c_2 are constants depending on the model and on the collider. Their values for the models discussed below are collected in Table I. $M_{Z'}(R_0)$ gives the $M_{Z'}$ bound when the bound on R is R_0. Equation (1) reflects the approximate logarithmic dependence of $M_{Z'}$ on R, which is mainly due to the structure-function behavior (and to the Z' propagator). The values of the constants $M_{Z'}(R_0)$, c_1, and c_2 result from a fit to the curves $R(M_{Z'})$ [which is proportional to $\sigma(Z')B(Z'\to l^+l^-)$ for a constant K factor] for the

TABLE I. $M_{Z'}(R_0)$ bounds in GeV for $R<R_0=0.025$ (0.01) at $Sp\bar{p}S$ (Tevatron) for the models described in the text. The fitting values of c_1 and c_2 are also given for the different models, as well as the values of the parameters fixing the gauge couplings to fermions.

Model	CERN $M_{Z'}(R_0)$ (GeV)	CERN $-c_1$	CERN c_2	Fermilab $M_{Z'}(R_0)$ (GeV)	Fermilab $-c_1$	Fermilab c_2	$\theta_2\in\left[-\frac{\pi}{2},\frac{\pi}{2}\right]$	$\lambda\geq 1$	$\theta_1\in\left[-\frac{\pi}{2},\frac{\pi}{2}\right]$
$Z_\chi^{(b)}$	177	0.404	0.014	295	0.552	0.074	$\arcsin\sqrt{5/8}$	1	
Z_ψ	181	0.409	0.014	298	0.564	0.080	$\arcsin\sqrt{3/8}$	1	
$Z_\eta^{(a)}$	173	0.437	0.015	271	0.617	0.098	0	1	
Z_{LR}	189	0.405	0.017	313	0.560	0.074	$\arcsin\sqrt{5/8}$	1.877	$\arcsin\sqrt{2/5}$
Z_1	206	0.385	0.014	351	0.540	0.056			
$Z_\chi^{(c)}$	164	0.441	0.014	261	0.600	0.097	$-\arcsin\sqrt{5/8}$	1	
Z_{B3}	189	0.393	0.011	319	0.538	0.068	$\arcsin\sqrt{5/8}$	1.371	1.195
Z_{B4}	186	0.387	0.011	317	0.529	0.068	$\arcsin\sqrt{5/8}$	1.179	-1.019
Z_{B7}	171	0.414	0.018	283	0.565	0.078	$\arcsin\sqrt{5/8}$	1.080	1.174
Z_{B8}	182	0.393	0.013	307	0.538	0.070	$\arcsin\sqrt{5/8}$	1.227	-0.686
$Z_{C1,\ldots,C5,D}$	179	0.402	0.011	299	0.546	0.073	$\arcsin\sqrt{5/8}$	1.045	-0.886

different models and colliders. The fitted curves were calculated using Duke and Owens (DO) structure functions, set 1.[15,16] The fit was performed in the region

$$R \in [0.0015, 0.15] \ (R \in [0.0006, 0.06]) \tag{3}$$

for S$p\bar{p}$S (Tevatron).

Although c_1 and c_2 are model dependent, their dependence is small enough to allow for a common fit to all models:

$$c_1(\text{S}p\bar{p}\text{S}) = -0.405, \quad c_2(\text{S}p\bar{p}\text{S}) = 0.013 , \tag{4}$$

and

$$c_1(\text{Tevatron}) = -0.555 , \quad c_2(\text{Tevatron}) = 0.075 . \tag{5}$$

This common fit results in small errors at the end of the R range ($<2\%$ for S$p\bar{p}$S and $<3\%$ for Tevatron) except for models Z_η and $Z_{\chi'}$, where the errors are a bit larger ($<2.8\%$ for S$p\bar{p}$S and $<5.5\%$ for Tevatron). The quadratic dependence in Eq. (1) is introduced to have a good fit in a larger R interval. However, for the S$p\bar{p}$S collider a linear fit [$c_2=0$ in Eq. (3)] would give a good enough description of the curves.

For the present limit at the S$p\bar{p}$S, $R<R_0=0.025$ [$\sigma(Z)B(Z\to l^+l^-)=72$ pb],[5,17] the $M_{Z'}$ bound can be read off from the first column in the table. For the Tevatron, after three months and with a luminosity of 10 pb^{-1}yr^{-1},[12] the expected bound on $R<R_0=0.01$ (Ref. 18) will provide the bound on the Z' mass quoted in the fourth column of the table. For R values in the range of Eq. (3), Eq. (1) gives a good approximation. For instance, if no events are seen at the Collider Detector Facility (CDF) at Fermilab at the end of 1989 (1992), leading to an integrated luminosity of about 5 pb^{-1} (15 pb^{-1}), the bounds on $M_{Z'}$ in column 4 of the table would increase. In particular, the lowest bound in the table, $M_{Z^{(c)}_{\chi'}}>261$ GeV will increase by 17% (50%), due to the factor

$$1-0.600\log_{10}\frac{0.0053\ (0.0018)}{0.01} +0.097\left[\log_{10}\frac{0.0053\ (0.0018)}{0.01}\right]^2 = 1.17\ (1.50) \tag{6}$$

in Eq. (1), to 306 GeV (392 GeV).

Although a detailed discussion of the different models (and of the former parametrization) is given in Ref. 20, we summarize it here. The models in the table correspond to different values of the parameters in the Lagrangian

$$L_{\text{NC}} = eJ^\mu_{\text{EM}}A_\mu + \frac{e}{s_W c_W}J^\mu_Z Z_\mu + \frac{e}{c_W}J^\mu_{Z'}Z'_\mu ; \tag{7}$$

$$J_{\text{EM}} = J_1 + (\tfrac{5}{3})^{1/2}J_2 ,$$

$$J_Z = c_3 J_{Z^0} - s_3 J_{Z^{0\prime}} , \tag{8}$$

$$J_{Z'} = s_3 J_{Z^0} + c_3 J_{Z^{0\prime}} ;$$

$$J_{Z^0} = J_1 - s_W^2 J_{\text{EM}} , \tag{9}$$

$$J_{Z^{0\prime}} = (\tfrac{5}{3})^{1/2}\left[s_1c_1\left[\lambda - \frac{1}{\lambda}\right]J_2 + \left[\frac{c_1^2}{\lambda}+s_1^2\lambda\right](-c_2J_3+s_2J_4)\right] , \tag{10}$$

where s_i (c_i)$=\sin\theta_i$ ($\cos\theta_i$), s_W (c_W)$=\sin\theta_W$ ($\cos\theta_W$) (the electroweak angle), e is the electromagnetic constant, and J_i are the currents associated with the E_6 orthogonal generators $(T_i)=(T_{3L}, Y, Y', Y'')$ (these are explicitly given in Table 2 of Ref. 4). θ_3 gives the Z^0Z' mixing and it is fixed to zero, since it is experimentally known to be quite small. For a detailed discussion of (7)–(10) see also Ref. 4. Models $Z_{\chi,\psi,\eta,LR,1}$ (Refs. 2, 12, and 13) and $Z_{\chi'}$ (Ref. 14) in the table do not include renormalization effects. If $\sin^2\theta_W=0.23$, as we assume here,[21] these models do not unify in the minimal cases.[10] Z_ψ does not appear to descend from superstrings. $g_L=g_R$ for Z_{LR} implies $\lambda = [\frac{3}{2}(1-2s_W^2)]^{1/2}/s_W = 1.877$. Z_1 is a generic extra U(1) with the same quantum numbers as the observed Z but a different mass. ($Z_{\eta,\chi,\chi'}$ [(a),(b),(c), respectively] were also discussed in Refs. 4, 5, 22, and 23.) Finally, models $Z_{B3,\ldots,D}$ correspond to the different E_6 superstring-inspired models with an extra U(1) at low energy.[10] The λ,θ_1 values are fixed demanding unification and assuming a minimal content.[10,11,20]

As can be seen in the table the collider bounds on $M_{Z'}$ are not very model dependent.[5] This is so for the models considered for we are only dealing with total cross sections. [Asymmetries (would) distinguish better between models.] On the other hand, although the parameters λ and θ_1 for models $Z_\chi^{(b)},\ldots,Z_{\chi'}^{(c)}$ might look as good as others, they do not allow for unification to happen (for $\sin^2\theta_W=0.23$). Thus by including the renormalization-group constraints many fewer models are allowed, in particular, $Z_{B3},\ldots,Z_D$. We observe in the table that models $Z_{C1,\ldots,C5,D}$ provide a common prediction for λ, θ_1, and $M_{Z'}$. The reason is that the value $\sin^2\theta_W=0.23$ corresponds, for those models, to the case in which the intermediate scale coincides with the unification scale (M_X), and the renormalization from M_X to M_Z goes through in the same way for all of them. A (numerically) important ingredient for evaluating $R(M_{Z'})$ is the Z' width. We make the plausible (and conservative) assumption, given the relatively low $M_{Z'}$ bounds, that Z' can decay only into the standard fermions (including the top-quark contribution for $m_t=80$ GeV). A quantitative discussion of the Z' width dependence is given in Refs. 5 and 20.

Our results for the CERN and Fermilab colliders coincide with those of Ref. 5 for models (a),(b),(c). The small systematic difference among the $M_{Z'}(R_0)$ bounds might be traced back to the different methods for evaluating the total Z' cross sections. We have used an accurate numerical multivariable integration routine.

It must be emphasized that although for some models indirect $M_{Z'}$ bounds are more stringent[22,24] (as it can be seen by comparing the S$p\bar{p}$S bounds in the table to those quoted in Refs. 5 and 12), direct production bounds will be better in the near future.[25]

Experimentalists may prefer to incorporate the models into their Monte Carlo calculations. However, if the experimental value of R is appropriately corrected to take into account the features of the detector (e.g., efficiency,. . .), Eq. (1) gives an immediate bound on $M_{Z'}$. For any new experimental value of R Eq. (1) is used, and a new bound $M_{Z'}(R)$ is obtained. A similar analysis for the future hadron colliders, Serpukhov's UNK, the Large Hadron Collider (LHC), and the Superconducting Super-collider (SSC), can be found in Ref. 20.

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