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The CDF and D0 data of nearly 475 pb^{-1} in the dilepton channel is used to probe a recent class of models, Stueckelberg extensions of the standard model (StSM), which predict a Z' boson whose mass is of topological origin with a very narrow decay width. A Drell-Yan analysis for dilepton production via this Z' shows that the current data put constraints on the parameter space of the StSM. With a total integrated luminosity of 8 fb^{-1}, the very narrow Z' can be discovered up to a mass of about 600 GeV. The StSM Z' will be very distinct since it can occur in the region where a Randall-Sundrum graviton is excluded.

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Introduction.—In this Letter we investigate the implications of the cumulative CDF [1] and D0 [2] data in the dilepton channel to probe the very narrow Z' boson that arises in the $U(1)_X$ Stueckelberg extension of the standard model (StSM) [3]. Thus string models involving dimensional reduction and intersecting D branes [4] allow for the possibility of an Abelian gauge boson gaining mass without the benefit of a Higgs phenomenon via the Stueckelberg mechanism where the mass parameter is topological in nature [5]. Indeed the Stueckelberg couplings have played an important role in the D brane model building [6]. The topological mass scale can be obtained from dimensional reduction and is typically the size of the compactification scale [4]. However, it could also be taken as an independent parameter [7]. The model of Ref. [3] involves a nontrivial mixing of the Stueckelberg and the standard model (SM) sectors via an additional term $\mathcal{L}_{\rm St}$ in the low energy effective Lagrangian so that

$$\mathcal{L}_{\rm St} = -\frac{C_{\mu\nu}C^{\mu\nu}}{4} + g_X C_\mu \mathcal{J}_X^\mu - \frac{1}{2}(\partial_\mu \sigma + M_1 C_\mu + M_2 B_\mu)^2, \quad (1)$$

where C_μ is the gauge field for $U(1)_X$ and $\mathcal{J}_X^\mu$ gives coupling to the hidden sector (HS) but has no coupling to the visible sector (VS), B_μ is the gauge field associated with $U(1)_Y$, σ is the axion, and M_1 and M_2 are mass parameters that appear in the Stueckelberg extension. After electroweak symmetry breaking with a single Higgs doublet, the gauge group $SU(2)_L \times U(1)_Y \times U(1)_X$ breaks down to $U(1)_{em}$, and the neutral sector is modified due to mixing with the Stueckelberg sector. The mass^2 matrix in the neutral sector is a 3×3 matrix and in the basis $(C^\mu, B^\mu, A^{3\mu})$ is given by

$$M_{\rm St}^2 = \begin{pmatrix} M_1^2 & M_1 M_2 & 0 \\ M_1 M_2 & \frac{1}{4}v^2 g_Y^2 + M_2^2 & -\frac{1}{4}v^2 g_2 g_Y \\ 0 & -\frac{1}{4}v^2 g_2 g_Y & \frac{1}{4}v^2 g_2^2 \end{pmatrix}, \quad (2)$$

where $g_2(g_Y)$ are the gauge couplings in the $SU(2)_L \times [U(1)_Y]$ sectors, and $v = \langle H \rangle$ where H is the SM Higgs field. $M_{\rm St}^2$ being real and symmetric is diagonalized by an orthonormal matrix O so that $O^T M_{\rm St}^2 O = M_{\rm St-diag}^2$ with the useful parametrization

$$O = \begin{pmatrix} c_\psi c_\phi - s_\theta s_\phi s_\psi & -s_\psi c_\phi - s_\theta s_\phi c_\psi & -c_\theta s_\phi \\ c_\psi s_\phi + s_\theta c_\phi s_\psi & -s_\psi s_\phi + s_\theta c_\phi c_\psi & c_\theta c_\phi \\ -c_\theta s_\psi & -c_\theta c_\psi & s_\theta \end{pmatrix}. \quad (3)$$

One then finds $t_\phi = M_2/M_1$, $t_\theta = g_Y c_\phi / g_2$, and $t_\psi = t_\theta t_\phi M_W^2 (c_\theta [M_{Z'}^2 - M_W^2(1 + t_\theta^2)])^{-1}$, where $s_\theta = \sin\theta$, $c_\theta = \cos\theta$, $t_\theta = \tan\theta$, etc. Equation (2) contains one massless state, i.e., the photon, and two massive states, i.e., the Z and Z'. The photon field here is a linear combination of C^μ, B^μ, $A^{3\mu}$ which distinguishes it from other class of extensions [see, e.g., [8–10]], and in addition the model contains a very narrow Z' resonance. The effects of the Stueckelberg extension are contained in the parameters $\epsilon \equiv M_2/M_1$ and M_1. In the limit $\epsilon \to 0$ the Stueckelberg sector decouples from the standard model.

Electroweak constraints.—To determine the allowed corridors in ϵ and M_1, we follow a similar approach as in the analysis of Refs. [11,12] used in constraining the size of extra dimensions. We begin by recalling that in the on-shell scheme the W boson mass including loop corrections is given by [13]

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2} G_F \sin^2\theta_W (1 - \Delta r)}, \quad (4)$$

where the Fermi constant G_F and the fine structure constant α (at $Q^2 = 0$) are known to a high degree of accuracy. The quantity Δr is the radiative correction and is determined so that $\Delta r = 0.0363 \pm 0.0019$ [14], where the uncertainty comes from error in the top mass and from the error in $\alpha(M_Z^2)$. Now since in the on-shell scheme $\sin^2\theta_W = (1 - M_W^2/M_Z^2)$ one may use Eq. (4) and the current experimental value of $M_W = 80.425 \pm 0.034$ [14] to make a prediction of M_Z. Such a prediction within SM is in excellent agreement with the current experimental value of $M_Z = 91.1876 \pm 0.0021$. Thus the above analysis requires that the effects of the Stueckelberg extension on the

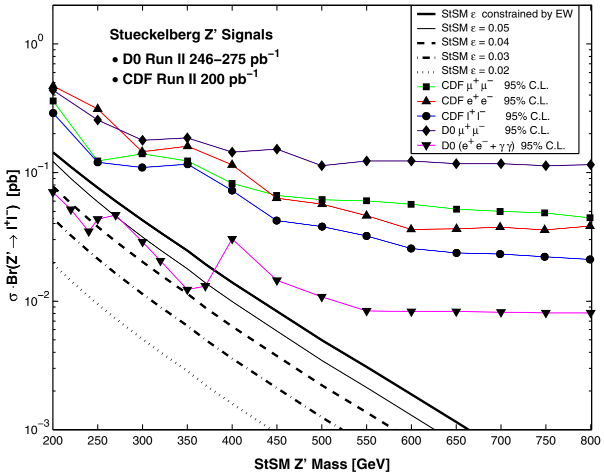

FIG. 1 (color online). Z' signal in StSM using the CDF [1] and D0 [2] data. The data put a lower limit of about 250 GeV on $M_{Z'}$ for $\epsilon \approx 0.035$ and 375 GeV for $\epsilon \approx 0.06$.

Z mass must be such that they lie in the error corridor of the SM prediction. We now calculate the error δM_Z in the SM prediction of M_Z in order to limit ϵ. From Eq. (4) we find that $\delta \equiv \delta M_Z/M_Z|_{\rm SM}$ is given by

$$\delta = \sqrt{\left(\frac{1 - 2\sin^2\theta_W}{\cos^3\theta_W}\frac{\delta M_W}{M_Z}\right)^2 + \frac{\tan^4\theta_W(\delta\Delta r)^2}{4(1-\Delta r)^2}}. \qquad (5)$$

From Eq. (2) the Stueckelberg correction to the Z mass in the region $M_1^2 \gg M_Z^2$ is given by $|\Delta M_Z/M_Z| = \frac{1}{2}\sin^2\theta_W(1 - M_Z^2/M_1^2)^{-1}\epsilon^2$. Equating this shift to the result of Eq. (5) one finds an upper bound on ϵ

$$|\epsilon| \lesssim 0.061\sqrt{1 - (M_Z/M_1)^2}. \qquad (6)$$

Next we obtain in an independent way the constraint on ϵ by using a fit to a standard set of electroweak parameters. We follow closely the analysis of the LEP Working Group [14] [see also Refs. [15,16]], except that we will use the vector (v_f) and axial vector (a_f) couplings for the fermions in the StSM. Here, we exhibit as an example, the Z couplings of the charged leptons in the StSM

$$v_\ell(a_\ell) = \sqrt{\rho_\ell}(T_{3,\ell}\beta_L - Q_\ell(\beta_L \pm \beta_R)\kappa_\ell s_W^2), \qquad (7)$$

where $\beta_{L,R}$ are as defined in Ref. [3], and where ρ_ℓ and κ_ℓ (in general complex valued quantities) contain radiative corrections from propagator self-energies and flavor specific vertex corrections and are as defined in Refs. [14,17]. The SM limit corresponds to $\epsilon \to 0$, and $\beta_{L,R} \to 1$.

Using the above modifications we have carried out a fit in the electroweak sector. Results of the analysis are given in Table I for $M_1 = 250$ GeV and ϵ in the range (0.035–0.057) where the upper limit corresponds to Eq. (6) and the lower limit yields $|\Delta\text{Pull}| < 1$. To indicate the quality of the fits we compute $\chi^2/\text{DOF} = (20.1, 16.2, 18.4)/18$ for $\epsilon = (0.057, 0.035, 0.0)$ excluding $A_{\rm FB}^{(0,b)}$ and $\chi^2/\text{DOF} = (43.3, 28.0, 25.0)/19$ including $A_{\rm FB}^{(0,b)}$ (where DOF repre-

TABLE I. Results of the StSM fit to a standard set of electroweak observables at the Z pole for ϵ in the range (0.035–0.057) for $M_1 = 250$ GeV. The Pulls are calculated as shifts from the SM fit via $\Delta\text{Pull} = (\text{SM} - \text{StSM})/\delta\,\text{exp}$ and Pull(StSM) = Pull(SM) + ΔPull. The data in column 2 are taken from Ref. [18].

Quantity	Value (Experiment)	StSM	ΔPull
Γ_Z [GeV]	2.4952 ± 0.0023	(2.4948–2.4935)	(0.4, 0.9)
$\sigma_{\rm had}$ [nb]	41.541 ± 0.037	(41.478–41.481)	(−0.1, −0.1)
R_e	20.804 ± 0.050	(20.743–20.742)	(−0.1, −0.2)
R_μ	20.785 ± 0.033	(20.744–20.743)	(0.1, 0.2)
R_τ	20.764 ± 0.045	(20.791–20.790)	(0.0, 0.1)
R_b	0.21643 ± 0.00072	(0.21583–0.21583)	(0.0, 0.0)
R_c	0.1686 ± 0.0047	(0.1723–0.1723)	(0.0, 0.0)
$A_{\rm FB}^{(0,e)}$	0.0145 ± 0.0025	(0.0167–0.0174)	(−0.2, −0.5)
$A_{\rm FB}^{(0,\mu)}$	0.0169 ± 0.0013	(0.0167–0.0174)	(−0.3, −0.9)
$A_{\rm FB}^{(0,\tau)}$	0.0188 ± 0.0017	(0.0167–0.0174)	(−0.3, −0.7)
$A_{\rm FB}^{(0,b)}$	0.0991 ± 0.0016	(0.1046–0.1068)	(−0.9, −2.2)
$A_{\rm FB}^{(0,c)}$	0.0708 ± 0.0035	(0.0748–0.0764)	(−0.3, −0.7)
$A_{\rm FB}^{(0,s)}$	0.098 ± 0.011	(0.105–0.107)	(−0.1, −0.3)
A_e	0.1515 ± 0.0019	(0.1492–0.1524)	(−1.0, −2.7)
A_μ	0.142 ± 0.015	(0.149–0.152)	(−0.1, −0.3)
A_τ	0.143 ± 0.004	(0.149–0.152)	(−0.5, −1.3)
A_b	0.923 ± 0.020	(0.935–0.935)	(0.0, 0.0)
A_c	0.671 ± 0.027	(0.668–0.668)	(0.0, 0.0)
A_s	0.895 ± 0.091	(0.936–0.936)	(0.0, 0.0)

sents degrees of freedom). We note that $\epsilon = 0.035$ gives the same excellent fit to the data as $\epsilon = 0$ [SM [14]] case including or excluding $A_{\rm FB}^{(0,b)}$. For $\epsilon = 0.057$ the fit excluding $A_{\rm FB}^{(0,b)}$ is as good as for the SM case, but less so when one includes $A_{\rm FB}^{(0,b)}$. However, as is well known $A_{\rm FB}^{(0,b)}$ is also problematic in SM since it has a large Pull. Thus Ref. [14] quotes the Pull for $A_{\rm FB}^{(0,b)}$ in the range $[-2.5, -2.8]$ and states that the large shift could be due to a fluctuation in one or more of the input measurements in their experimental fits. It is also stated in Ref. [17] that at least some of the problem here may be experimental. Thus it would appear that the determination of $A_{\rm FB}^{(0,b)}$ is on a somewhat less firm footing than the other electroweak parameters.

The Stueckelberg extension of the standard model is among a class of models where such an extension can occur. Other examples are provided by the extension $SU(2)_L \times U(1)_R \times U(1)_{B-L} \times U(1)_X$, or by the extension of the more popular $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ left-right (LR) model [19] to give the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_X$ (StLR). Here the mixing matrix is still a consequence of Eq. (1) except that B_μ now stands for the $U(1)_{B-L}$ gauge field. The vector mass^2 matrix in this case is 4×4 involving the fields (C_μ, B_μ, $A^3_{\mu L}$, $A^3_{\mu R}$). The mass^2 matrix leads to one massless state and three massive states Z, Z', Z''. It is easily checked that the electromagnetic interaction is given by $\mathcal{L}_{\rm EM} = eA^\gamma_\mu(\mathcal{J}^\mu_{B-L} + \mathcal{J}^{3\mu}_{2L} + \mathcal{J}^{3\mu}_{2R})$, where

$$\frac{1}{e^2} = \frac{1}{g^2}\left(1 - \frac{M_2^2}{M_1^2}\right) + \frac{1}{g_Y^2}\left(1 + \frac{M_2^2}{M_1^2}\right) \tag{8}$$

and where g_Y is related to $g = g_{2L} = g_{2R}$ and g' by $1/g_Y^2 = 1/g^2 + 1/g'^2$. The above relations limit to the standard LR relation as $M_2/M_1 \to 0$. Quite remarkably, the Z' couplings of StLR are very close to the Z' couplings of StSM and thus we will focus the analysis on StSM and the results for the StLR will be very similar.

Drell-Yan analysis of Stueckelberg Z'.—Next we discuss the production of the narrow Z' by the Drell-Yan process at the Tevatron. For the hadronic process $A + B \to V + X$, and the partonic subprocess $q\bar{q} \to V \to l^+l^-$, the dilepton production differential cross section to leading order (Born) is given by

$$\frac{d\sigma_{\rm AB}}{dM^2} = \frac{1}{s}\sum_q \sigma^{q\bar{q}}(M^2)\mathcal{W}_{\{{\rm AB}(q\bar{q})\}}(\tau), \qquad \tau = M^2/s$$

$$\mathcal{W}_{\{{\rm AB}(q\bar{q})\}}(\tau) = \int_0^1\int_0^1 dxdy\,\delta(\tau - xy)\mathcal{P}_{\{{\rm AB}(q\bar{q})\}}(x, y),$$

$$\mathcal{P}_{\{{\rm AB}(q\bar{q})\}}(x, y) = f_{q,A}(x)f_{\bar{q},B}(y) + f_{\bar{q},A}(x)f_{q,B}(y).$$

Here $f_{q,A}$ and $f_{\bar{q},A}$ are parton distribution functions (PDFs). $\sigma^{q\bar{q}}$ is given in [3]. $\frac{d\sigma_{p\bar{p}}}{dM^2}$ may be calculated via a perturbative expansion in the strong coupling, α_s, which is conventionally absorbed into the Drell-Yan K factor as discussed in detail in Refs. [8,9,15,20].

In Fig. 1 we give an analysis of the Drell-Yan cross section for the process $p\bar{p} \to Z' \to l^+l^-$ as a function of $M_{Z'}$. The analysis is done at $\sqrt{s} = 1.96$ TeV, using the CTEQ5L [21] PDFs with a flat K factor of 1.3 for the appropriate comparisons with other models and with the CDF [1] and D0 [2] combined data in the dilepton channel. Remarkably one finds that the Stueckelberg Z' for the case $\epsilon \approx 0.06$ is eliminated up to about 375 GeV with the current data (at 95% C.L.). This lower limit decreases as ϵ decreases but the current data still constrain the model up to $\epsilon \approx 0.035$. This result is in contrast to the LR, E_6, and to the little Higgs models [22] where the Z' boson has already been eliminated up to (610–815) GeV with the CDF [1] and D0 [2] data. In Fig. 2 we give the analysis of the discovery limit for the Stueckelberg Z' with an integrated luminosity of 8 fb^{-1}. Here we have extrapolated the experimental sensitivity curves for the $\mu^+\mu^-$ and for the more sensitive $e^+e^- + \gamma\gamma$ channel downwards by a factor of $1/\sqrt{N}$ where N is the ratio of the expected integrated luminosity to the current integrated luminosity. The analysis shows that a Stueckelberg Z' can be discovered up to a mass of about 600 GeV and if no effect is seen one can put a lower limit on the Z' mass at about 600 GeV. In Fig. 3 we give the exclusion plots in the $\epsilon - M_{Z'}$ plane using the current data and also using the total integrated luminosity of 8 fb^{-1} expected at the Tevatron. An analysis including hidden sector with $\Gamma_{\rm HS} = \Gamma_{\rm VS}$ is also exhibited. The exclusion plots show that even the hidden sector is beginning to be constrained and these constraints will become even more severe with future data.

Conclusion.—The type of Z' boson that arises from the mixing of the standard model with the Stueckelberg sector

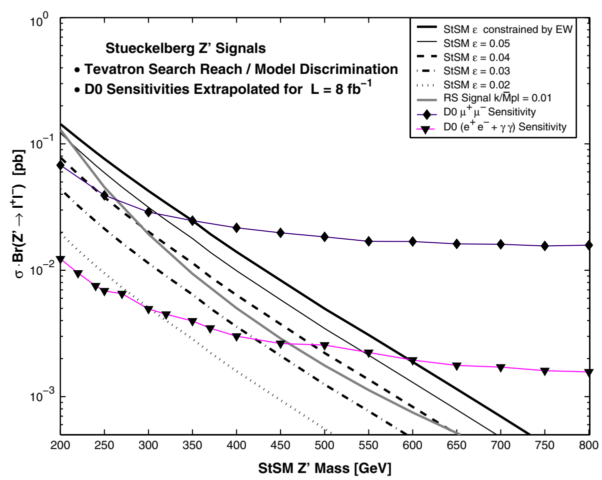

FIG. 2 (color online). Z' signal in StSM with 8 fb^{-1} of data using an extrapolation of the sensitivity of the D0 [2] detector for the $\mu^+\mu^-$ and $e^+e^- + \gamma\gamma$ modes. The data will put a lower limit of about 600 (300) GeV on $M_{Z'}$ mass for $\epsilon = 0.06(0.02)$. Also plotted for comparison is $\sigma{\rm Br}\,(G \to l^+l^-)$ for the RS case.

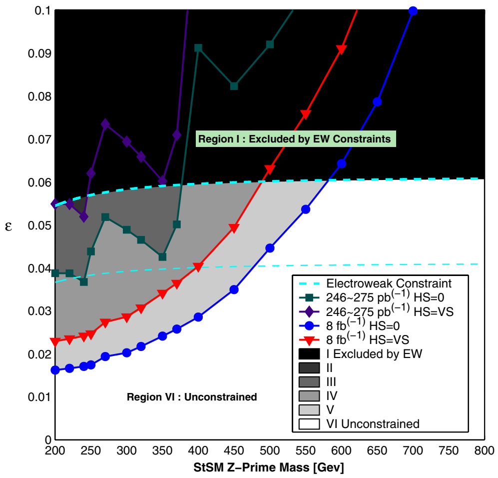

FIG. 3 (color online). Exclusion plots in the $\epsilon - M_{Z'}$ plane utilizing the more sensitive D0 [2] $e^+e^- + \gamma\gamma$ mode with (a) the 246–275 pb^{-1} of data, and (b) 8 fb^{-1} of data where an extrapolation of the sensitivity curve is used. The upper dashed curve is the maximum value of ϵ allowed by Eq. (6) and the lower dashed curve corresponds to $|\Delta\text{Pull}| < 1$ (see the text for the validity of imposing the lower constraint). Cases with (without) a hidden sector are shown. Regions II, III, IV, and V are constrained by the conditions given at their respective boundaries.

is very different from the Z' bosons that normally arise in grand unified models [8] and in string models such as [10], or in Kaluza-Klein excitations of the Z in the compactifications of large extra dimensions [23]. The distinguishing feature is that the decay width in the present case is exceptionally narrow with width ≤ 60 MeV for $M_{Z'} \leq 1$ TeV. It is interesting to note that there is a region of the parameter space where a Stueckelberg Z' boson may be mistaken for a narrow resonance of a Randall-Sundrum (RS) [24] warped geometry. The RS warped geometry is a slice of anti−de Sitter space (AdS_5) with the metric $ds^2 = \exp(-2kr_c|\phi|)\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2$, $0 \leq \phi \leq \pi$, where r_c is the radius of the extra dimension and k is the curvature of AdS_5. The overlap of $\sigma\text{Br}(Z' \to l^+l^-)$ and $\sigma\text{Br}(G \to l^+l^-)$ for the RS graviton is shown in Fig. 2 for the case $k/\bar{M}_{\text{Pl}} = 0.01$, where $\bar{M}_{\text{Pl}} = M_{\text{Pl}}/\sqrt{8\pi}$ is the reduced Planck mass. However, the constraints of the precision electroweak data actually eliminate the RS graviton in this case [2,25]. Thus if a resonance effect is seen in the dilepton mass range of up to about 600 GeV in the CDF and D0 data at the predicted level, the Stueckelberg Z' would be a prime candidate since the RS graviton possibility is absent in this case.

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