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0031-9007/09/102(9)/091805(7)

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We present a search for high-mass neutral resonances using dimuon data corresponding to an integrated luminosity of 2.3 fb^{-1} collected in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV by the CDF II detector at the Fermilab Tevatron. No significant excess above the standard model expectation is observed in the dimuon invariant-mass spectrum. We set 95% confidence level upper limits on $\sigma\text{BR}(p\bar{p} \rightarrow X \rightarrow \mu\bar{\mu})$, where X is a boson with spin-0, 1, or 2. Using these cross section limits, we determine lower mass limits on sneutrinos in R-parity-violating supersymmetric models, Z' bosons, and Kaluza-Klein gravitons in the Randall-Sundrum model.

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Neutral resonances decaying to muons have historically been a source of major discoveries. They also occur in a variety of theoretical models which attempt to unify the standard model (SM) forces or explain the large gap between the SM and gravitational energy scales. The gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ of the SM can be embedded in larger gauge groups such as $SU(5)$, $SO(10)$, and E_6, to achieve unification in a grand unified theory [1–4]. In many schemes of grand unified theory symmetry breaking, $U(1)$ gauge groups survive to relatively low energies [2], leading to the prediction of neutral gauge vector (Z') bosons. Such Z' bosons typically couple with electroweak strength to SM fermions, and can be observed at hadron colliders as narrow, spin-1, dimuon resonances from $q\bar{q} \rightarrow Z' \rightarrow \mu\bar{\mu}$. Many other models, such as the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge group of the left-right model [5], and the "little Higgs" models [6,7], also predict heavy neutral gauge bosons.

Additional spatial dimensions are a possible explanation for the gap between the electroweak symmetry-breaking scale and the gravitational energy scale $M_{\rm Planck}$ [8,9]. The Randall-Sundrum (RS) model [9] predicts excited Kaluza-Klein modes of the graviton, which appear as spin-2 resonances G^* in the process $q\bar{q} \rightarrow G^* \rightarrow \mu\bar{\mu}$. These modes have a narrow intrinsic width when $k/M_{\rm Planck} < 0.1$, where k^2 is the spacetime curvature in the extra dimension. In superstring theories with $\mathcal{O}(1)$ couplings, $k/M_{\rm Planck} \approx 0.01$ [10].

Spin-0 resonances such as the sneutrino $\tilde{\nu}$ in the process $q\bar{q} \rightarrow \tilde{\nu}, \bar{\tilde{\nu}} \rightarrow \mu\bar{\mu}$ are predicted by supersymmetric theories with R-parity violation [11]. Scalar Higgs bosons can be produced as resonances and decay to dimuons.

The most sensitive direct searches for high-mass boson resonances, which have previously been performed at the Tevatron, have set 95% confidence level (C.L.) lower limits on the masses $M_{Z'}$, M_{G^*}, and $M_{\tilde{\nu}}$ of Z' bosons, RS gravitons, and sneutrinos, respectively. The previous dimuon publication from CDF II, based on $\approx$200 pb^{-1} of integrated luminosity [12], set mass limits that vary from 170 to 885 GeV [13] depending on the boson spin and couplings to the SM fermions. Other dilepton and diphoton decay channels have also been explored at the Tevatron [14,15]. Using an order of magnitude more data, we present in this Letter the most sensitive direct search to date for Z', G^*, and $\tilde{\nu}$ bosons at high mass.

This analysis uses 2.3 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV in the CDF II detector [16,17]. CDF II is a magnetic spectrometer surrounded by calorimeters and muon detectors. We use the central drift chamber (COT) [18], the central calorimeter [19], and the muon detectors [20] for identification and measurement of muons with $|\eta| < 1$ [13]. The online selection requires a COT track with $p_T > 18$ GeV [13], and matching muon detector hits. We select a pair of oppositely charged muons, each with a COT track with $p_T > 30$ GeV passing quality requirements, and a minimum-ionization signal in the calorimeter. Cosmic rays are rejected using COT hit timing [21]. The dimuon signal sample consists of 68 150 events in the control region $70 < m_{\mu\bar{\mu}} < 100$ GeV, where the $p\bar{p} \rightarrow Z \rightarrow \mu\bar{\mu}$ process dominates, and 3804 events in the search region $m_{\mu\bar{\mu}} > 100$ GeV.

The alignment of the COT is performed using a pure sample of high-momentum cosmic-ray muons, in order to obtain the best possible dimuon mass resolution. Each muon's complete trajectory is fitted to a single helix [21]. The fits are used to determine the relative locations of the sense wires, including gravitational and electrostatic displacements, with a statistical accuracy of a few microns [17]. We constrain remaining misalignments, which cause a bias in the track curvature, by comparing $\langle E/p \rangle$ [13] for electrons and positrons. The tracker momentum scale and resolution are measured by template fitting the $Z \rightarrow \mu\bar{\mu}$ mass peak, and calibrating to the world average values [22] of the Z boson mass and width.

For a resonance with electroweak coupling and mass above 200 GeV, the observed width of the $m_{\mu\bar{\mu}}$ distribution is dominated by the track curvature resolution, resulting in an approximately constant resolution of $\delta m_{\mu\bar{\mu}}^{-1} \approx 0.17$ TeV^{-1}. Our search strategy is to construct templates of the observable $m_{\mu\bar{\mu}}^{-1}$ distribution for a range of boson Breit-Wigner pole masses, add the background distributions to the templates, and compare the templates to the $m_{\mu\bar{\mu}}^{-1}$ distribution from the data in the search region $m_{\mu\bar{\mu}} > 100$ GeV. The simulated templates (including backgrounds) are normalized to the data in the $70 < m_{\mu\bar{\mu}} < 100$ GeV region, thus canceling several sources of systematic uncertainty.

We determine the most likely number of signal events (N_S), and the corresponding confidence intervals [23], from the binned Poisson likelihood [17] for the observed data to be produced by a sum of signal and background templates. The use of the constant-resolution variable $m_{\mu\bar{\mu}}^{-1}$ simplifies the optimization of the template binning and the scan over the boson pole masses.

Signal and SM Drell-Yan background distributions are evaluated using a specialized Monte Carlo simulation [17] of boson production and decay, and of the detector response to the leptons and hadrons. The kinematics of boson production and decay are obtained from the PYTHIA [24] event generator using the CTEQ6M [25] set of parton distribution functions. QED radiation is simulated [17] based on the WGRAD program [26]. The Monte Carlo program performs a detailed hit-level simulation of the lepton tracks. COT hits are generated according to their resolution ($\approx$150 μm) and measured efficiencies, and a helix fit is

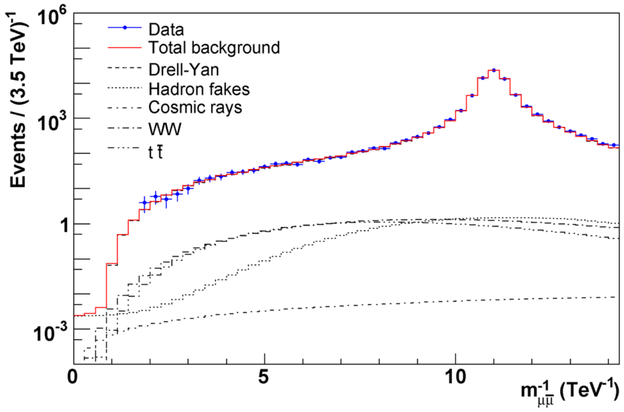

FIG. 1 (color online). The distribution of $m_{\mu\bar{\mu}}^{-1}$ (TeV^{-1}) for the observed data (points), the individual backgrounds (dotted or dashed histograms) and the summed background (solid histogram). The Z boson peak is prominently seen. The inverse mass distribution has the useful feature that the detector resolution is constant (≈ 0.17 TeV^{-1}) over the range shown in the plot.

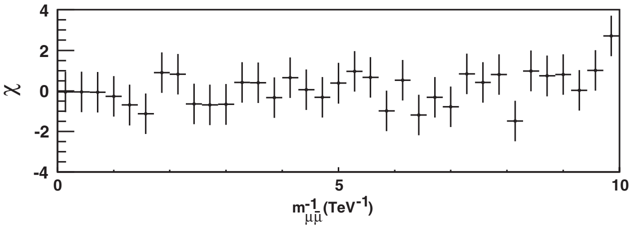

FIG. 2. The difference between the distributions of $m_{\mu\bar{\mu}}^{-1}$ (TeV^{-1}) for the observed data and the summed background, divided by the expected statistical uncertainty in each bin. All vertical error bars have unit size.

performed (as it is in data) to simulate the reconstructed track. We apply a mass-dependent next-to-next-to-leading order (NNLO) multiplicative correction (K factor) [27] to the SM Drell-Yan background.

The SM production processes for W^+W^- [28] and $t\bar{t}$ [29] have small contributions, and are evaluated using their NLO cross sections, PYTHIA, and a detector simulation based on GEANT [30]. Misidentification backgrounds result from cosmic rays, QCD jets, and π/K decays in flight (DIF). We evaluate the cosmic-ray background using a large sample of cosmic rays identified with the COT-timing-based algorithm [21], and using the direction-of-flight information provided by this algorithm. The $m_{\mu\bar{\mu}}^{-1}$ shape of misidentified jets is evaluated from a large sample of inclusive jet events. Decays in flight within the COT active volume generate a kink along the helical trajectory, resulting in a mismeasurement of the track curvature. For large reconstructed momenta, the measured DIF curvature distribution is approximately uniform and leads to a flat $m_{\mu\bar{\mu}}^{-1}$ spectrum. Most DIF tracks are rejected using their abnormal COT-hit pattern and large fit χ^2. The jet and DIF backgrounds are normalized using the mass distribution of same-charge dimuon events.

Figure 1 shows the $m_{\mu\bar{\mu}}^{-1}$ distributions of the observed data and the expected backgrounds, which are in good agreement (as shown in Fig. 2). A resonance whose observed width is dominated by detector resolution would appear as a peak spanning approximately three bins. The likelihood-based fitter finds no significant excess. We use background-only ensembles of simulated events, each with the statistics of the data sample, to evaluate the probability of statistical fluctuations anywhere in the search region generating a discrepancy at least as significant as the largest discrepancy found in the data. We find this probability ("p value") to be 6.6% and we conclude that the observed data are statistically consistent with the SM expectation. The dielectron m_{ee} spectrum from 2.5 fb^{-1} of CDF II data [31] shows that the largest discrepancy with the expected background occurs at $m_{ee} \sim 240$ GeV. Figure 2 shows that the dimuon data are consistent with the expectation near this mass to better than 1σ in statistical precision. The sensitivity of the dielectron analysis for a spin-1 resonance at this mass is $\approx 20\%$ better than the dimuon analysis reported here.

The likelihood fitter determines the 95% C.L. upper limit on the number of signal events, for each value of the resonance pole mass. We convert these limits to limits on $\sigma\text{BR}(\tilde{\nu}, \bar{\tilde{\nu}} \rightarrow \mu\bar{\mu})$, $\sigma\text{BR}(Z' \rightarrow \mu\bar{\mu})$, and $\sigma\text{BR}(G^* \rightarrow \mu\bar{\mu})$ using the total acceptance as a function of pole mass, the NNLO cross section for $Z \rightarrow \mu\mu$ of 251.3 pb [16], and dividing by the observed number of $Z \rightarrow \mu\bar{\mu}$ events. The acceptance is verified with the detailed GEANT-based simulation, and comparisons to data distributions. The muon identification efficiency is verified using a pure data sample of Z bosons triggered by one identified muon. The total acceptance, including kinematic and fiducial acceptance and dimuon identification, increases from $\approx 13\%$ ($\approx 20\%$) for a pole mass of 90 GeV to $\approx 40\%$ ($\approx 45\%$) for a Z' (graviton) pole mass of 1 TeV, and decreases for higher pole masses due to the kinematic limit of the parton collisions. The 95% C.L. upper limits on $\sigma\text{BR}(\tilde{\nu}, \bar{\tilde{\nu}} \rightarrow \mu\bar{\mu})$, $\sigma\text{BR}(Z' \rightarrow \mu\bar{\mu})$, and $\sigma\text{BR}(G^* \rightarrow \mu\bar{\mu})$ are shown in Fig. 3. The dominant mass-dependent systematic uncertainties arise from parton distribution functions (16%), the NNLO K factor (9%) [27], QED radiative corrections (3%) [32], and acceptance (3%), all quoted at 1 TeV. These uncertainties are incorporated as functions of $m_{\mu\bar{\mu}}$ and increase monotonically beyond 100 GeV. Uncertainties on the momentum scale and resolution, and on the non-Drell-Yan background predictions, have a negligible effect.

Our signal templates have been generated with a resonance pole width $\Gamma = 2.8\% \times M$, based on the SM Z boson width. Thus our signal scan probes an observed width of $\approx [17\%(M/\text{TeV}) \oplus 2.8\%]M$. In a model where the observed width increases by a factor x, the cross section limits would increase by about a factor of $\sqrt{x}$.

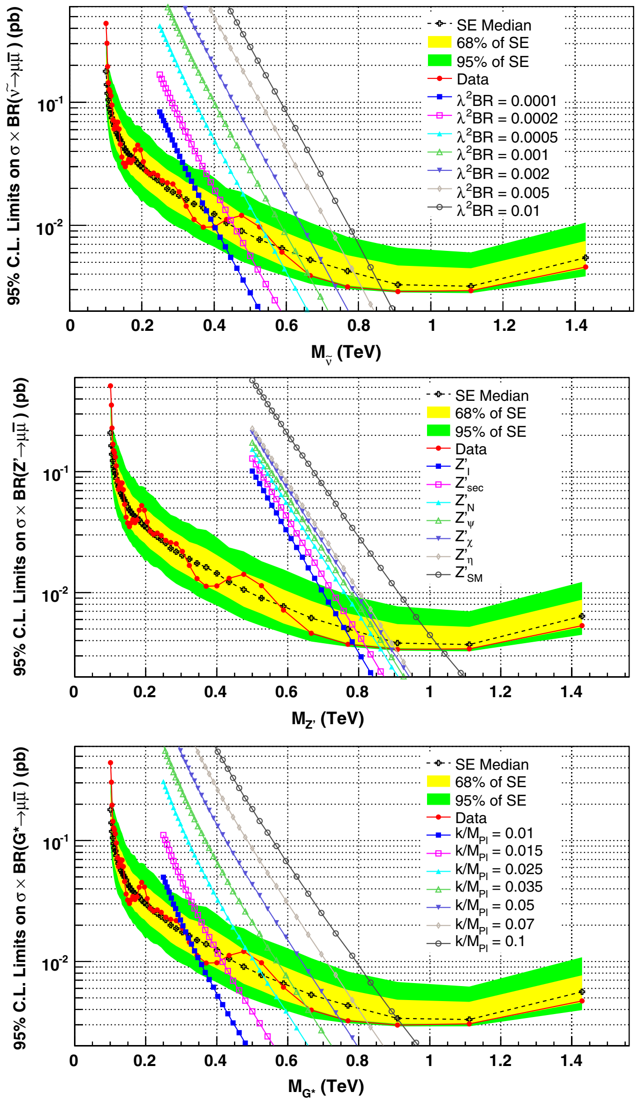

FIG. 3 (color online). The 95% C.L. upper limits on $\sigma\text{BR}(\tilde{\nu}, \bar{\tilde{\nu}} \to \mu\bar{\mu})$ vs $M_{\tilde{\nu}}$ (top), $\sigma\text{BR}(Z' \to \mu\bar{\mu})$ vs $M_{Z'}$ (middle), and $\sigma\text{BR}(G^* \to \mu\bar{\mu})$ vs M_{G^*} (bottom). Also shown are the theoretical cross sections for various model parameter values [9,11,33]. The expected limits and ranges of limits, as derived from simulated experiments (SE), are shown for comparison. The step size between adjacent templates in the signal scan is 0.2 TeV^{-1} in pole mass.

TABLE I. 95% C.L. lower limits on Z', graviton, and sneutrino masses (in GeV) for various model parameters [9,11,33]. For the R-parity-violating sneutrino model, λ is the $d\bar{d}\,\tilde{\nu}$ coupling, and BR denotes the $\tilde{\nu}, \bar{\tilde{\nu}} \to \mu\bar{\mu}$ branching ratio.

Z' Model	Z' Mass limit	RS graviton k/M_{Planck}	Graviton Mass limit	$\tilde{\nu}$ λ^2BR	$\tilde{\nu}$ Mass limit
Z'_I	789	0.01	293	0.0001	397
Z'_{sec}	821	0.015	409	0.0002	441
Z'_N	861	0.025	493	0.0005	541
Z'_ψ	878	0.035	651	0.001	662
Z'_χ	892	0.05	746	0.002	731
Z'_η	904	0.07	824	0.005	810
Z'_{SM}	1030	0.1	921	0.01	866

We use PYTHIA to compute the cross sections for production of Z' bosons predicted by E_6 models [33] or having the same couplings to SM fermions as the Z boson, and of G^* bosons for various k/M_{Planck} values. We apply the NNLO K factor to these leading order cross sections. The NLO $\tilde{\nu}$ production cross sections are obtained from [11]. We derive the boson mass limits shown in Table I.

In conclusion, we have presented a direct search for high-mass neutral resonances with spin-0, 1, and 2, using an integrated luminosity of 2.3 fb^{-1} collected by the CDF II detector. Our dimuon invariant-mass spectrum is consistent with the SM expectation. We set the world's tightest constraints on Z' bosons in various models, on Kaluza-Klein graviton modes in the RS model, and on sneutrinos in R-parity-violating supersymmetric models. At 95% C.L., we exclude $100 < M_{Z'} < 982$ GeV for a Z'_η boson of the E_6 model, $100 < M_{G^*} < 921$ GeV for $k/M_{\text{Planck}} = 0.1$, and $100 < M_{\tilde{\nu}} < 810$ GeV for $\lambda^2\text{BR}(\tilde{\nu}, \bar{\tilde{\nu}} \to \mu\bar{\mu}) = 0.01$, where λ is the $d\bar{d}\,\tilde{\nu}$ coupling and BR denotes the $\tilde{\nu}, \bar{\tilde{\nu}} \to \mu\bar{\mu}$ branching ratio.

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[1] J. L. Rosner, Phys. Rev. D **35**, 2244 (1987).

[2] F. del Aguila, M. Quiros, and F. Zwirner, Nucl. Phys. **B287**, 419 (1987); J. L. Hewett and T. G. Rizzo, Phys. Rep. **183**, 193 (1989).

[3] J. Erler *et al.*, Phys. Rev. D **66**, 015002 (2002); T. Han *et al.*, Phys. Rev. D **70**, 115006 (2004).

[4] J. Kang and P. Langacker, Phys. Rev. D **71**, 035014 (2005).

[5] R. N. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 566 (1975); G. Senjanovic and R. N. Mohapatra, Phys. Rev. D **12**, 1502 (1975); R. N. Mohapatra and G. Senjanovic, Phys. Rev. D **23**, 165 (1981).

[6] N. Arkani-Hamed *et al.*, J. High Energy Phys. 07 (2002) 034.

[7] T. Han *et al.*, Phys. Rev. D **67**, 095004 (2003).

[8] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, Phys. Lett. B **429**, 263 (1998).

[9] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 4690 (1999); L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999).

[10] H. Davoudiasl, J. L. Hewett, and T. G. Rizzo, Phys. Rev. Lett. **84**, 2080 (2000).

[11] D. Choudhury, S. Majhi, and V. Ravindran, Nucl. Phys. **B660**, 343 (2003); We assume the $\tilde{\nu}$ and $\tilde{\bar{\nu}}$ have equal masses and couplings and contribute equally to a potential signal, as in W. Shao-Ming, H. Liang, M. Wen-Gan, Z. Ren-You, and J. Yi, Phys. Rev. D **74**, 057902 (2006).

[12] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **95**, 252001 (2005).

[13] We use the convention $\hbar = c = 1$. Pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle from the beam axis. Track momentum p transverse to the beam is denoted p_T. E denotes the calorimeter energy.

[14] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **99**, 171802 (2007); T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **99**, 171801 (2007); A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **96**, 211801 (2006); D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **95**, 131801 (2005).

[15] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **100**, 091802 (2008).

[16] A. Abulencia *et al.* (CDF Collaboration), J. Phys. G **34**, 2457 (2007); D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, 091803 (2005).

[17] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **77**, 112001 (2008).

[18] T. Affolder *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **526**, 249 (2004).

[19] F. Abe *et al.* (CDF Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **271**, 387 (1988).

[20] G. Ascoli *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **268**, 33 (1988).

[21] A. V. Kotwal, H. K. Gerberich, and C. Hays, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 110 (2003).

[22] S. Schael *et al.* (ALEPH, DELPHI, L3, OPAL, and SLD Collaborations), Phys. Rep. **427**, 257 (2006), and references therein.

[23] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).

[24] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994). We use PYTHIA version 6.208.

[25] J. Pumplin *et al.*, J. High Energy Phys. 07 (2002) 012.

[26] U. Baur, S. Keller, and D. Wackeroth, Phys. Rev. D **59**, 013002 (1998).

[27] M. Carena, A. Daleo, B. A. Dobrescu, and T. M. P. Tait, Phys. Rev. D **70**, 093009 (2004).

[28] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999). We use MCFM version 3.4.5 from mcfm.fnal.gov.

[29] R. Bonciani, S. Catani, M. L. Mangano, and P. Nason, Nucl. Phys. **B529**, 424 (1998); M. Cacciari *et al.*, J. High Energy Phys. 04 (2004) 068.

[30] R. Brun and F. Carminati, CERN Program Library Long Writeup, W5013, 1993, version 3.15 (unpublished).

[31] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **102**, 031801 (2009).

[32] U. Baur, O. Brein, W. Hollik, C. Schappacher, and D. Wackeroth, Phys. Rev. D **65**, 033007 (2002), Fig. 3(b).

[33] The couplings we use are detailed in C. Ciobanu *et al.*, FERMILAB Report No. FERMILAB-FN-0773-E, 2008.