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We present a search for high-mass neutral resonances using dimuon data corresponding to an integrated luminosity of $2.3 \, \text{fb}^{-1}$ 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 $\sigma \times \text{BR}(p\bar{p} \to X \to \mu\mu)$, 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, $Z^0$ bosons, and Kaluza-Klein gravitons in the Randall-Sundrum model.
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 $q\bar{q} \rightarrow Z' \rightarrow \mu\mu$. Many other models, such as the $SU(2)_L \times SU(2)_R \times U(1)_{L-R}$ 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 $M_{\text{Planck}}$ [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 $q\bar{q} \rightarrow G^* \rightarrow \mu\mu$. These modes have a narrow intrinsic width when $k/M_{\text{Planck}} < 0.1$, where $k^2$ is the spacetime curvature in the extra dimension. In superstring theories with $O(1)$ couplings, $k/M_{\text{Planck}} = 0.01$ [10].

Spin-0 resonances such as the neutrino $\nu$ in the process $q\bar{q} \rightarrow \nu\bar{\nu}, \nu \rightarrow \mu\mu$ 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 $M_{\nu}$ of $Z'$ bosons, RS gravitons, and sneutrinos, respectively. The previous dimuon publication from CDF II, based on $=200$ 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 $\nu$ 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 $70 < m_{\mu\mu} < 100$ GeV, where the $p\bar{p} \rightarrow Z \rightarrow \mu\mu$ process dominates, and 3804 events in the search region $m_{\mu\mu} > 100$ 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 $(E/p)$ [13] for electrons and positrons. The tracker momentum scale and resolution are measured by template fitting the $Z \rightarrow \mu\mu$ 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 $m_{\mu\mu}$ distribution is dominated by the track curvature resolution, resulting in an approximately constant resolution of $\delta m_{\mu\mu} = 0.17$ TeV$^{-1}$. Our search strategy is to construct templates of the observable $m_{\mu\mu}$ distribution for a range of boson Breit-Wigner pole masses, add the background distributions to the templates, and compare the templates to the $m_{\mu\mu}$ distribution from the data in the search region $m_{\mu\mu} > 100$ GeV. The simulated templates (including backgrounds) are normalized to the data in the $70 < m_{\mu\mu} < 100$ 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 $m_{\mu\mu}$ 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 ($=150$ μm) and measured efficiencies, and a helix fit is
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 $\pi/K$ 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 ofinclusive 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 $\chi^2$. 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 ≈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 $\sigma BR(\tilde{\nu}, \tilde{\nu} \rightarrow \mu\bar{\mu})$, $\sigma BR(Z' \rightarrow \mu\bar{\mu})$, and $\sigma BR(G' \rightarrow \mu\bar{\mu})$ using the total acceptance as a function of pole mass, the NNLO cross section for $Z \rightarrow \mu\bar{\mu}$ 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 ≈13% (=20%) for a pole mass of 90 GeV to ≈40% (=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 $\sigma BR(\tilde{\nu}, \tilde{\nu} \rightarrow \mu\bar{\mu})$, $\sigma BR(Z' \rightarrow \mu\bar{\mu})$, and $\sigma BR(G' \rightarrow \mu\bar{\mu})$ 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 $= [17\%(M/{\text{TeV}}) \Phi 2.8\%] M$. In a model where the observed width increases by a factor $x$, the cross section limits would increase by about a factor of $\sqrt{x}$.
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 $k/M_{\text{Planck}}$ 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 $100 < M_{\tilde{\nu}} < 982$ GeV for a $Z'$ 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 $\lambda^2\text{BR}(\tilde{\nu}, \tilde{\nu} \to \mu \bar{\mu}) = 0.01$, where $\lambda$ is the $d\bar{d} \tilde{\nu}$ coupling and BR denotes the $\tilde{\nu} \to \mu \bar{\mu}$ branching ratio.

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**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, $\lambda$ is the $d\bar{d} \tilde{\nu}$ coupling, and BR denotes the $\tilde{\nu} \to \mu \bar{\mu}$ branching ratio.

| Model | Mass limit $k/M_{\text{Planck}}$ | $\lambda^2\text{BR}$ | $\tilde{\nu}$ mass limit |
|-------|----------------------------------|----------------------|-------------------------|
| $Z'_0$ | 789 | 0.01 | 293 | 0.0001 | 397 |
| $Z'_\text{sec}$ | 821 | 0.015 | 409 | 0.0002 | 441 |
| $Z'_0$ | 861 | 0.025 | 493 | 0.0005 | 541 |
| $Z'_\text{sec}$ | 878 | 0.035 | 651 | 0.001 | 662 |
| $Z'_0$ | 892 | 0.05 | 746 | 0.002 | 731 |
| $Z'_\text{sec}$ | 904 | 0.07 | 824 | 0.005 | 810 |
| $Z'_\text{SM}$ | 1030 | 0.1 | 921 | 0.01 | 866 |

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Figure 1: The potential of a scalar field in the presence of a vector field.

The potential is given by:

\[ V(x) = \frac{k}{x^2} \]

where the constant \( k \) is determined by fitting the data. The vector field is described by the following metric:

\[ g_{\mu\nu} = \begin{pmatrix} 1 & 0 \\ 0 & -e^{2\phi(x)} \end{pmatrix} \]

where \( \phi(x) \) is the scalar field and \( e \) is the fine-structure constant. The field equations are

\[ \Box \phi = 0 \]

\[ \Box A_\mu = 0 \]

where \( \Box = \nabla^\mu \nabla_\mu \) is the d'Alembert operator.

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