# A search for high-mass resonances decaying to dimuons at CDF

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## Abstract

We present a search for 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 $\sigma \cdot BR(p\bar{p} \to X \to \mu\bar{\mu})$, where $X$ is a boson with spin 0, 1, or 2. Using these cross section limits, we determine lower mass limits on $Z'$ bosons, Kaluza-Klein gravitons in the Randall-Sundrum model, and sneutrinos in $R$-parity-violating supersymmetric models.



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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 scales. The gauge group $SU(3) \times SU(2) \times U(1)$ 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 (GUT) [1–4]. In many schemes of GUT symmetry-breaking, $U(1)$ gauge groups survive to relatively low energies [2], leading to the prediction of neutral gauge vector bosons, generically referred to as $Z'$ bosons. Such $Z'$ bosons typically couple with electroweak strength to SM fermions, thus appearing at hadron colliders as narrow, spin-1, dimuon resonances from $q\bar{q} \to Z' \to \mu\bar{\mu}$. Many other models, such as the $SU(2)_L \times SU(2)_R \times U(1)$ 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]. In the Randall-Sundrum (RS) scenario [9], the ground-state wave function of the graviton is localized on a three-dimensional "brane" separated in a fourth spatial dimension from the SM brane. The space-time metric varies exponentially in the fourth dimension, causing the wave-function overlap with the SM brane to be exponentially suppressed and explaining the apparent weakness of gravity and the large value of $M_{\text{Planck}}$. This model predicts excited Kaluza-Klein modes of the graviton which are localized on the SM brane. These modes appear as spin-2 resonances $G^*$ in the process $q\bar{q} \to G^* \to \mu\bar{\mu}$, with a narrow intrinsic width when $k/M_{\text{Planck}} < 0.1$, where $k^2$ is the spacetime curvature in the extra dimension.

Spin-0 resonances such as $q\bar{q} \to \tilde{\nu} \to \mu\bar{\mu}$ are predicted by supersymmetric theories with $R$-parity violation, where $R$-parity is a multiplicative quantum number that is conserved in interactions with an even number of supersymmetric particles. In addition, scalar Higgs bosons in the SM and its extensions 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 analysed $\approx 200$ pb$^{-1}$ of data [10], setting limits that vary from 170 GeV to 885 GeV depending on the boson spin and couplings to the SM fermions. Other dilepton and diphoton decay channels have also been explored at the Tevatron [11, 12]. In this Letter, we present using an order of magnitude more data, the most sensitive direct search to date for $Z'$, $G^*$, and $\tilde{\nu}$ bosons, over most of the parameter space.

This analysis uses data corresponding to an integrated luminosity of 2.3 $\mathrm{fb}^{-1}$, collected in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV by the CDF II detector [13, 14] at the Tevatron. CDF II is a magnetic spectrometer surrounded by calorimeters and muon detectors. We use the central drift chamber (COT) [15], the central calorimeter [16] and the muon detectors [17] for identification and measurement of muons with $|\eta| < 1$ [18]. The online muon event selection (trigger) requires a COT track with $p_T > 18$ GeV [18], and matching muon detector hits. In the analysis, we select muons 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 [19]. The dimuon signal sample consists of 68150 events in the dimuon invariant mass control region $70 < m_{\mu\bar{\mu}} < 100$ GeV, where the $p\bar{p} \to Z \to \mu\bar{\mu}$ process dominates, and 3804 events in the search region $m_{\mu\bar{\mu}} > 100$ GeV.

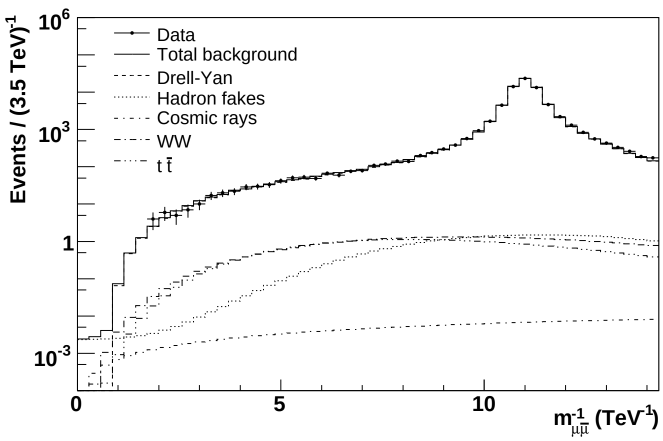


FIG. 1: The distribution of $m_{\mu\bar{\mu}}^{-1}$ (TeV$^{-1}$) for the data (points), the individual backgrounds (dotted or dashed histograms) and the summed background (solid histogram). The $Z$ boson peak is prominently seen. The inverse mass distribution has the useful feature that the detector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

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 [19]. 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. We constrain remaining misalignments, which cause a bias in the track curvature, by comparing $\langle E/p \rangle$ [18] for electrons and positrons. The tracker momentum scale and resolution is measured by template-fitting the $Z \to \mu\bar{\mu}$ mass peak, and calibrating to the world average values [24, 25] 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 GeV $< m_{\mu\bar{\mu}} <$ 100 GeV region, thus cancelling several sources of systematic uncertainty.

We determine the most likely number of signal events ($N_S$), and the corresponding confidence intervals [20], from the binned Poisson likelihood [13] for the 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.

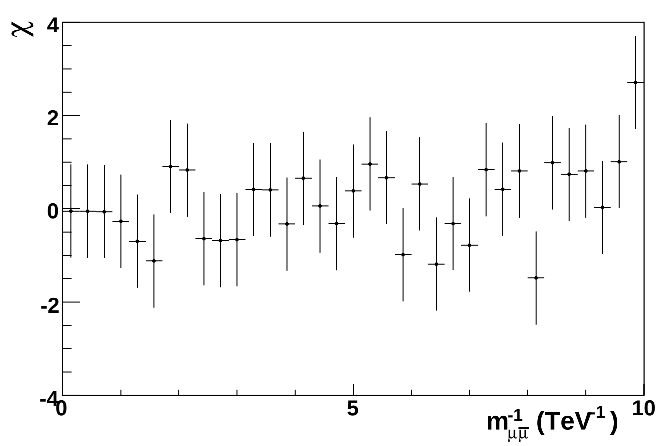


FIG. 2: The difference between the distributions of $m_{\mu\bar{\mu}}^{-1}$ (TeV$^{-1}$) for the data and the summed background, divided by the expected statistical uncertainty in each bin. All vertical error bars have unit size. The p-value of the largest deviation (which occurs at $m_{\mu\bar{\mu}} \sim 103$ GeV as seen above) is 6.6%.

Signal and SM Drell-Yan background distributions are evaluated using a specially written Monte Carlo (MC) simulation [13] of boson production and decay, and of the detector response to the leptons and the hadronic activity in the event. The kinematics of boson production and decay are obtained from the PYTHIA [21] event generator using the CTEQ6M [22] set of parton distribution functions. QED radiation is simulated according to the WGRAD program [23]. The MC performs a detailed hit-level simulation of the lepton tracks. COT hits are generated according to their resolution ($\approx 150\ \mu$m) 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) [26] to the SM Drell-Yan background.

The SM production processes for $W^+W^-$ [27] and $t\bar{t}$ [28] have small contributions, and are evaluated using PYTHIA and a detector simulation based on GEANT [29]. Misidentification backgrounds result from cosmic rays, QCD jets, and $\pi/K$ decays-in-flight (DIF). We evaluate the shape of the cosmic-ray background from a large sample of cosmic rays identified with the COT-timing-based algorithm [19], and normalize it to the data using events with large $\Delta t_0$, where $\Delta t_0$ is the difference between the muons' reconstructed time at the beam axis. The $m_{\mu\bar{\mu}}^{-1}$ shape of the background from 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. At the large reconstructed momenta relevant to this search, the measured DIF curvature distribution is approximately uniform and leads to a flat $m_{\mu\bar{\mu}}^{-1}$ spectrum. The kinks in DIF tracks allow most of them to be rejected using their abnormal COT-hit pattern and large $\chi^2$ of the track fit. The jet and DIF backgrounds are normalized using the number of same-charge dimuon events observed at low and high mass respectively.

Figure 1 shows the $m_{\mu\bar{\mu}}^{-1}$ distributions of the 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 data are statistically consistent with the SM expectation.

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 $\sigma \cdot BR(\tilde{\nu} \rightarrow \mu\bar{\mu})$, $\sigma \cdot BR(Z' \rightarrow \mu\bar{\mu})$ and $\sigma \cdot BR(G^* \rightarrow \mu\bar{\mu})$ using the total acceptance as a function of pole mass, and dividing by the observed number of $Z \rightarrow \mu\bar{\mu}$ events. The acceptance is verified with the detailed GEANT-based simulation of the detector, as well as comparisons to data distributions. The muon identification efficiency is cross-checked using a pure data sample of $Z$ bosons triggered by one identified muon. The simulation reproduces the muon efficiency as a function of muon $p_T$. The total acceptance, including kinematic and fiducial acceptance and dimuon identification efficiency, increases from $\approx 13\%$ at the $Z$ boson pole to $\approx 40\%$ for a $Z'$ pole mass of 1 TeV, and decreases for higher pole masses due to the kinematic limit of the parton collisions. The lepton $\eta$ [18] distribution obtained from spin-2 graviton decay is more central than the distribution obtained from spin-1 boson decay. The total acceptance for the graviton increases from $\approx 20\%$ for a pole mass of 90 GeV to $\approx 45\%$ for a pole mass of 1 TeV. The 95% C.L. upper limits on $\sigma \cdot BR(\tilde{\nu} \rightarrow \mu\bar{\mu})$, $\sigma \cdot BR(Z' \rightarrow \mu\bar{\mu})$, and $\sigma \cdot BR(G^* \rightarrow \mu\bar{\mu})$ are shown in Fig. 3 as functions of $M^{-1}$, where $M$ is the pole mass. The dominant mass-dependent systematic uncertainties arise from parton distribution functions (16%), the NNLO $K$-factor (9%) [26], QED radiative corrections (3%) [30], and acceptance (3%), all quoted at 1 TeV. These uncertainties are incorporated as functions of dimuon invariant mass and increase monotonically beyond the normalization region at 100 GeV. Uncertainties on the momentum scale and resolution, and on the non-Drell-Yan background predictions, have a negligible effect on the search.

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 multiplicative factor $x$, the cross section limits would increase by about a factor of $\sqrt{x}$.

We use PYTHIA to compute the theoretical cross sections for production of $Z'$ bosons predicted by $E_6$ models [32] or having the same couplings to SM fermions as the $Z$ boson, as well as $G^*$ production cross sections for various $k/M_{\text{Planck}}$ values. We apply the NNLO $K$-factor to these LO cross sections. The NLO $\tilde{\nu}$ production cross sections are obtained from [31]. From the intersection of the observed cross section limits and the theoretical cross section curves, we derive the lower limits on these boson masses shown in Table I.

| $Z'$ model | $Z'$ mass limit | RS graviton $k/M_{\text{Planck}}$ | graviton mass limit | $\tilde{\nu}$ $\lambda^2 \cdot BR$ | $\tilde{\nu}$ mass limit |
|---|---|---|---|---|---|
| $Z'_{sq}$ | 754 | 0.010 | 293 | 0.0001 | 278 |
| $Z'_I$ | 789 | 0.015 | 409 | 0.0002 | 397 |
| $Z'_N$ | 861 | 0.025 | 493 | 0.0005 | 457 |
| $Z'_\psi$ | 878 | 0.035 | 651 | 0.001 | 541 |
| $Z'_\chi$ | 892 | 0.05 | 746 | 0.002 | 662 |
| $Z'_\eta$ | 975 | 0.07 | 824 | 0.005 | 751 |
| $Z'_{SM}$ | 1030 | 0.1 | 921 | 0.01 | 810 |

TABLE I: 95% C.L. lower limits on $Z'$, graviton, and sneutrino masses (in GeV) for various model parameters [9, 31, 32]. 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.

In conclusion, we have presented a search for high-mass dimuon resonances with spin-0, 1, and 2, using data corresponding to an integrated luminosity of 2.3 fb$^{-1}$ collected by the CDF II detector at the Tevatron. Our dimuon invariant mass spectrum is consistent with the SM expectation. From this direct search for heavy neutral bosons, 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 $100 < M_{Z'} < 975$ GeV for a $Z'_\eta$ 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 $\lambda^2 \cdot BR(\tilde{\nu} \to \mu\bar{\mu}) = 0.01$, 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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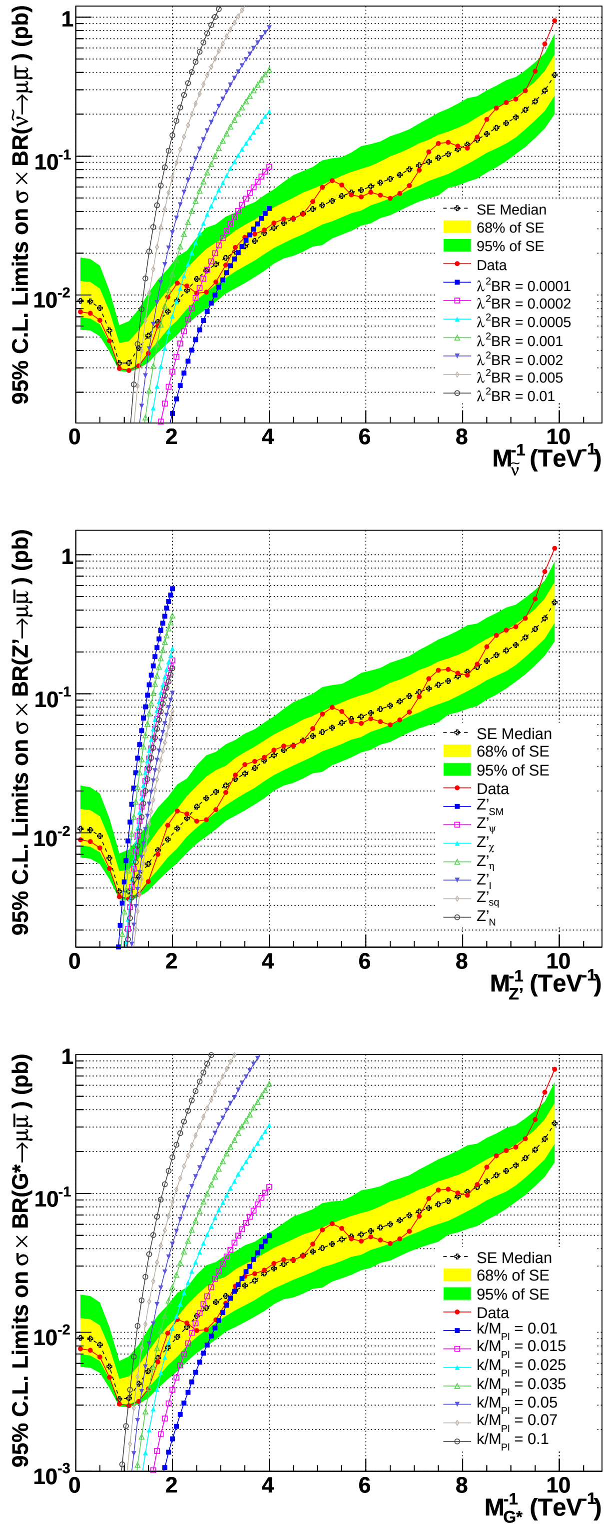


FIG. 3: The 95% C.L. upper limits on $\sigma \cdot BR(\tilde{\nu} \to \mu\bar{\mu})$ vs $M_{\tilde{\nu}}^{-1}$ (top), $\sigma \cdot BR(Z' \to \mu\bar{\mu})$ versus $M_{Z'}^{-1}$ (middle), and $\sigma \cdot BR(G^* \to \mu\bar{\mu})$ versus $M_{G^*}^{-1}$ (bottom). Also shown are the theoretical cross sections for various model parameter values [9, 31, 32]. The expected limits and ranges of limits, as derived from simulated experiments (SE), are shown for comparison.