**Search for High Mass Resonances Decaying to Muon Pairs in s=1.96TeV pp Collisions**

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Search for High Mass Resonances Decaying to Muon Pairs in $\sqrt{s} = 1.96$ TeV $pp$ Collisions


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We present a search for a new narrow, spin-1, high mass resonance decaying to $\mu^+\mu^- + X$, using a matrix-element-based likelihood and a simultaneous measurement of the resonance mass and production rate. In data with $4.6 \text{ fb}^{-1}$ of integrated luminosity collected by the CDF detector in $p\bar{p}$ collisions at $\sqrt{s} = 1960$ GeV, the most likely signal cross section is consistent with zero at 16% confidence level. We therefore do not observe evidence for a high mass resonance and place limits on models predicting spin-1 resonances, including $M > 1071$ GeV/c$^2$ at 95% confidence level for a $Z'$ boson with the same couplings to fermions as the $Z$ boson.

We report a search for a narrow spin-1 resonance ($Z'$) with decays to muon pairs and a mass between $130$ GeV/c$^2$ and $1$ TeV/c$^2$. Such a resonance is predicted generically in models with additional gauge groups [1], a feature of many extensions to the standard model of particle physics (SM). Typical examples are little Higgs models [2] and the next-to-minimal supersymmetric model [3]; models can also be framed generically to cover a large set of potential signals [4].

Current 95% confidence level (C.L.) lower limits on the mass of a $Z'$ boson with the same couplings to fermions as the $Z$ boson ($Z'_{\text{SM}}$) are $1030$ GeV/c$^2$ from a search of CDF dimuon data with $2.3 \text{ fb}^{-1}$ of integrated luminosity [5] and $1023$ [6] and $963$ GeV/c$^2$ [7] from respective searches in
dielectron data from D0 in 5.4 fb$^{-1}$ and from CDF in 2.5 fb$^{-1}$, respectively.

This Letter reports a new search of the CDF dimuon data, superseding Ref. [5], with several significant enhancements: twice the integrated luminosity, a matrix-element-based likelihood providing an approximately 20% relative increase in cross-section sensitivity at large $Z'$ mass, and a new statistical approach designed to maximize simultaneously both discovery potential and mass exclusion limits in searches for new physics. This new approach directly fits the data to a single $Z'$ boson hypothesis in the plane of boson mass and signal cross section and can be applied to any search for a hypothetical new particle of unknown mass.

We use a data sample corresponding to an integrated luminosity of 4.6 fb$^{-1}$, collected with the CDF II detector [8], a general purpose detector designed to study $p\bar{p}$ collisions at the Fermilab Tevatron. The tracking system consists of a cylindrical open-cell drift chamber and silicon microstrip detectors in a 1.4 T magnetic field parallel to the beam axis. The silicon detectors provide tracking information for pseudorapidity $|\eta| < 2$ [9] and are used to reconstruct collision and decay points. The drift chamber surrounds the silicon detectors and gives full coverage in the central pseudorapidity region ($|\eta| < 1$). For the muon kinematics relevant to this search, the tracker provides an invariant mass resolution of $\delta M/M^2 = 17\%/(\text{TeV}/c^2)$. Electromagnetic and hadronic calorimeters surrounding the tracking system measure energy from particle showers and minimum ionizing particles such as muons. Drift chambers and scintillators located outside the calorimeters detect muons in the central pseudorapidity region $|\eta| < 1$.

Events used for this search are selected on-line with a trigger requiring a muon candidate with $p_T > 18$ GeV/c. The event selection is unchanged from the previous search [5], requiring at least two oppositely charged muons with $p_T > 30$ GeV/c and no identified cosmic rays [10]. Each muon is required to have calorimeter deposits consistent with a minimum ionizing particle and have a track fully within the fiducial volume of the drift chamber. At least one muon must have an associated muon-chamber track.

The dominant and irreducible background is standard model $Z/\gamma^*$ production with subsequent decay to muons. We model this background by using events generated at leading order by PYTHIA [11] with the CTEQ6L [12] parton distribution functions (PDFs). Events are reweighted by the ratio of next-to-next-to-leading-order to leading-order cross sections as a function of dimuon mass [4]. We use the standard CDF simulation [13] to model the detector response to the particles in the event. The overall normalization of this background is derived from the data near the $Z$ boson pole mass: $70 < M_{\mu\mu} < 110$ GeV/$c^2$.

The remaining background contributions are small relative to standard model sources of dimuons. Decays of $WW$ (1%) and $tt$ (1%) to dimuons are described by using PYTHIA and the CDF detector simulation, normalized to next-to-leading-order cross sections [14]. The background from objects misidentified as muons (0.5%) is estimated by using the distribution of calorimeter energy in the vicinity of each candidate muon in the sample [15]. Cosmic-ray backgrounds (~< 0.01%) are modeled by using identified cosmic-ray events, weighted by the probability to survive the cosmic-ray removal algorithm [10].

The observed spectrum of dimuon invariant mass ($M_{\mu\mu}$) is in good agreement with the total SM plus cosmic-ray prediction, as shown in Fig. 1. We expect $1851 \pm 90$ events with $M_{\mu\mu} > 130$ GeV/$c^2$ and observe 1813 events.

We model the production and decay of a spin-1 resonance $Z'_SM$ by using MADEVENT [16], assuming fermionic couplings equal to those of the $Z$ boson. Initial-state QCD radiation, hadronization, and showering are modeled with PYTHIA. The acceptance for $Z'$ boson events varies with invariant mass, increasing from 20% at 200 GeV/$c^2$ to nearly 40% at 1 TeV/$c^2$; for pole masses above $M_{\mu\mu} = 1$ TeV/$c^2$, the resonance peak is suppressed due to the lack of initial-state partons with sufficient momentum, leading to a drop in mean invariant mass and acceptance.

![FIG. 1 (color online). Top: The distributions of $M_{\mu\mu}$ for data with 4.6 fb$^{-1}$ of integrated luminosity (triangles) and expected SM backgrounds (histograms) with two example $Z'_SM$ signals. Bottom: The relative difference between observed and expected data, as a function of dimuon mass. Error bars show statistical uncertainty.](image-url)
The previous CDF search [5] used a binned likelihood fit with bins uniform in the inverse of the reconstructed dimuon mass to extract the best-fit signal cross section at a range of masses. That approach weighted events in the same reconstructed inverse mass bin equally, independent of expected track resolutions. We improve on this method by using an unbinned likelihood that includes a theoretical expression of expected track resolutions. We improve on this method by using an unbinned likelihood that includes a theoretical expression of expected track resolutions. We improve on this method by using an unbinned likelihood that includes a theoretical expression of expected track resolutions.

We refer to this as the 2D interval analysis. Second, we wish to discover the regions in \( M_{Z'} \) and cross section as a function of mass and to construct a 2D interval that gives a well-defined discovery condition. The joint likelihood is given by

\[
L(M_{Z'}, s_{Z'}) = \frac{(N_{bkg+Z})^n e^{-(N_{bkg+Z})}}{N!} \prod_i L(x_i|M_{Z'}, s_{Z'}),
\]

where \( M_{Z'} \) is the \( Z' \) pole mass, \( N \) is the number of events in the data, \( N_{Z'} (N_{bkg+Z}) \) is the number of events expected due to the \( Z' \) signal (and background), \( x_i \) represents the observed kinematics of the \( i \)th event, and \( s_{Z'} = \frac{N_{Z'}}{N_{bkg+Z}} \).

The dependence of the per-event likelihood is given by

\[
L(x_i|M_{Z'}, s_{Z'}) = s_{Z'} L_{Z'}(x_i|M_{Z'}) + (1 - s_{Z'}) L_{Z'/\gamma'}(x_i),
\]

and the likelihood \( L_{Z'} \) is calculated by integrating the matrix element for \( Z' \) production convolved with PDFs and the detector resolution functions:

\[
L_{Z'}(x_i = p_1, p_2, \sigma_{p1}, \sigma_{p2}, N_{jets}|M_{Z'}) = \int d\Phi(q_1, q_2) |\mathcal{M}_{Z'}(q_1, q_2, M_{Z'})|^2 f_{PDF}^p f_{PDF}^\mu \\
\quad \times T(p_1, q_1, \sigma_{p1}) T(p_2, q_2, \sigma_{p2}) P_{PT}(q_1 + q_2, N_{jets}),
\]

where \( p_1, p_2 \) represent the four-vectors of the two measured muons, \( q_1, q_2 \) represent the unknown four-vectors of the two true muons, \( \Phi \) represents phase space for the true muons, \( \mathcal{M} \) is the matrix element, and \( f_{PDF} \) is the parton distribution function [12]. \( T(p, q, \sigma_{p}) \) is the transfer function that parametrizes the detector resolution as a function of the measured uncertainty \( \sigma_{p} \), extracted from simulated data; the function uses two Gaussian functions in \( 1/p_T^\mu \), to describe the bulk and tail regions. \( P_{PT} \) is the probability density function for \( p_T \) of the \( \mu \mu \) system, parameterized in the number of jets \( (N_{jets}) \) with \( E_{TJET} > 15 \text{ GeV} \) and \( |\eta_{JET}| < 2.5 \), extracted from simulated samples with initial- and final-state radiation; the function uses two exponential functions in \( p_T^\mu \) to describe the bulk and tail regions. \( L_{Z'} \) is evaluated numerically by using importance-sampling techniques. The distributions of \( \sigma_{p} \) for the \( Z' \) signal and dominant \( Z/\gamma^* \) background are the same in the phase space region near the hypothesized \( Z' \) mass; thus, they do not affect the likelihood ratio ordering.

An analogous expression is used for \( L_{Z'/\gamma'} \), which describes the likelihood for the dominant \( Z/\gamma^* \) background. In simulated experiments, maximization of \( L(x_i|M_{Z'}, s_{Z'}) \) faithfully recovers the correct values of \( (M_{Z'}, s_{Z'}) \).

We analyze the resulting likelihood in two ways. First, we aim to discover the regions in \( (M_{Z'}, s_{Z'}) \) that are consistent with the data and inconsistent with the SM, making no assumptions about the relationship between \( M_{Z'} \) and \( s_{Z'} \). We refer to this as the 2D interval analysis. Second, we wish to set limits on the \( Z'/Z \) mass in specific models. In that case, we perform a raster scan, in which we choose a set of values of \( M_{Z'} \) and at each point derive limits on \( s_{Z'} \). Together with a prediction for \( s_{Z'}(M_{Z'}) \) in a specific theory, we can use the raster scan to place lower limits on \( M_{Z'} \).

The 2D interval is constructed via the unified ordering scheme [17] in two dimensions, resonance mass and cross section (see Fig. 2). At each test point in the \( (M_{Z'}, s_{Z'}) \) space, we calculate the ratio of the likelihood at the test point to the integrated luminosity. The solid circle indicates the best-fit value of \( (M_{Z'}, s_{Z'}) \) in the hypothesis that there is \( \sim 1 \) event in the bin.

FIG. 2 (color online). Observed 95% C.L. limits in 1D raster scan (top) and 2D intervals (bottom) for the data with 4.6 fb\(^{-1}\) of integrated luminosity. The solid circle indicates the best-fit value of \( (M_{Z'}, s_{Z'}) \) in the hypothesis that there is \( \sim 1 \) event in the bin.
point to the likelihood at the best-fit point where the likelihood is maximized. To determine which test points are consistent with the data at a given confidence level, we perform pseudoexperiments drawn from fully simulated samples over a grid of mass and $Z'$ signal cross section; these pseudoexperiments allow us to determine the fraction of pseudoexperiments which have a larger likelihood ratio. Test points which lie between the grid of simulated samples are interpolated between neighboring grid points. The pseudoexperiments include all backgrounds and interference effects between the $Z_0$ and $Z'$, as well as variation of the nuisance parameters from systematic uncertainties described below. This approach is well designed for discovery, as it tests the background hypothesis exactly once. The significance of an observation corresponds to the first confidence-level contour that includes exactly once. 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[1] P. Langacker, Rev. Mod. Phys. 81, 1199 (2009), and references therein.
[9] CDF uses a cylindrical coordinate system with the z axis along the proton beam axis. The pseudorapidity is η = −ln[tan(θ/2)], where θ is the polar angle relative to the proton beam direction and φ is the azimuthal angle, while p_T = |p|sinθ and E_T = E sinθ.