Search for New Physics in High Mass Electron-Positron Events in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report the results of a search for a narrow resonance in electron-positron events in the invariant mass range of $150 - 950 \text{ GeV}/c^2$ using $1.3 \text{ fb}^{-1}$ of $p\bar{p}$ collision data at $\sqrt{s} = 1.96 \text{ TeV}$ collected by the CDF II detector at Fermilab. No significant evidence of such a resonance is observed and we interpret the results to exclude the standard model-like $Z'$ with a mass below 923 GeV/$c^2$ and the Randall-Sundrum graviton with a mass below 807 GeV/$c^2$ for $k/\tilde{M}_{\text{pl}}=0.1$, both at the 95% confidence level. Combining with di-photon data excludes the Randall-Sundrum graviton for masses below 889 GeV/$c^2$ for $k/\tilde{M}_{\text{pl}}=0.1$.

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At hadron colliders, electron-positron pairs (ee) are a distinct experimental signature with a low background rate. Since many models introducing new physics beyond the standard model of particle physics (SM) predict an excess in ee production at a hadron collider, this channel has a strong discovery potential. This Letter describes a search for a new high mass state in ee events from pp collisions at √s = 1.96 TeV. The data used in this analysis were collected by the CDF II detector at the Fermiab Tevatron and correspond to an integrated luminosity of 260 pb$^{-1}$. The analysis also uses results from the γγ channel described in [1] to increase the analysis’s sensitivity to the Randall-Sundrum (RS) graviton [2].

The search is optimized for new physics processes which produce narrow ee resonances [3], but is otherwise model-independent. In addition to the above search, cross section times branching ratio (σ · B) upper limits [4] are set for generic neutral spin-1 and spin-2 bosons. These σ · B limits are then used to set lower bounds on the masses of specific particles predicted by new physics models. These particles are the $E_6$, $Z'$s [5] and the RS graviton. The $E_6$ model unifies the forces of the SM into the $E_6$ gauge group and in doing so predicts the presence of two additional neutral massive spin-1 bosons, referred to as $Z'$s, which can mix with some arbitrary mixing angle. The $Z''$, $Z'''$, $Z''''$, and $Z''''''$ correspond to specific values of the mixing angle and are used to benchmark the model. The RS graviton is predicted by the RS model of warped extra dimensions which solves the hierarchy between the weak and Planck scales by introducing an extra spatial dimension with negative curvature $k$. The model predicts a series of narrow neutral spin-2 resonances which couple to all SM particles, with the lowest mass resonance referred to here as the RS graviton. The properties of this model are determined by the mass of the RS graviton and the ratio $k/\bar{M}_{pl}$, where $\bar{M}_{pl}$ is the reduced effective Planck scale. This ratio governs the couplings of the graviton to SM particles and it has a favored range of 0.01 to 0.1 [6].

The most recent similar search by the DØ collaboration used an integrated luminosity of 260 pb$^{-1}$ and treated the ee and the di-photon (γγ) channels as a single channel to perform the first dedicated RS graviton search [3]. The most recent search for new physics in the ee channel by the CDF collaboration was a dedicated $Z'$ search and used an integrated luminosity of 448 pb$^{-1}$ [8].

This analysis is based on an integrated luminosity of 1.3 fb$^{-1}$ collected with the CDF II detector. The CDF II detector is a general purpose detector which is azimuthally and forward-backward symmetric and is described in detail elsewhere [6]. The relevant components for this analysis are the central tracking chamber (COT) and the central and plug calorimeters. The COT is a 96–layer drift chamber placed within a 1.4 Tesla magnetic field and is used to measure the momenta of charged particles within the pseudorapidity range $|\eta| \leq 1.1$ [10]. The central and plug calorimeters are sampling calorimeters that surround the COT; they consist of electromagnetic (EM) and hadronic sections that measure the energy of particles in the range $|\eta| \leq 1.1$ and $1.2 \leq |\eta| \leq 3.6$ respectively.

The trigger used in this analysis requires two separate deposits of EM energy in the calorimeter and is effectively 100% efficient for selecting ee events within the acceptance of the analysis. Events are selected by requiring two electron candidates with $E_T \geq 25$ GeV. Events are separated into two channels: central-central (CC) where both electrons are in the central EM calorimeter (CEM) ($|\eta| \leq 1.1$) and central-plug (CP) where one electron is in the plug EM calorimeter (PEM) ($1.2 \leq |\eta| \leq 3.0$). Electrons in the CEM are required to have a well–measured track, whereas there is no tracking requirement for electron candidates in the PEM. Due to the lack of tracking in the plug region there is no opposite sign requirement for any of the ee pairs. In the CC channel, 5% of the electron pairs in the signal region ($M_{ee} \geq 150$ GeV/$c^2$) are same sign, which is compatible with the fraction of misidentified opposite sign pairs predicted by simulation. Electrons are identified in an identical way to the previously published analysis [8], with the exception that a photon conversion veto is applied to central electrons in CP events. This selection cut improves the sensitivity of the analysis by reducing the γγ background in this channel. The event selection and the search method defined later were chosen without regard to events observed in the signal region to ensure a statistical robust result.

The geometric and kinematic acceptance as a function of resonance mass is estimated using event samples generated by Monte Carlo (MC) simulation. The PYTHIA event generator [12], with the CTEQ5L parton distribution functions (PDF) [13] and the CDF II detector simulation based on GENIE [3, 14] are used to generate all simulation samples unless otherwise stated. A $Z'$ with the couplings of the SM $Z$ (SM-like $Z'$) is used for the simulated spin-1 signal sample and a RS graviton with $k/\bar{M}_{pl} = 0.1$ is used for the spin-2 sample. Both the $Z'$ and RS graviton bosons are constrained to be within
The SM Drell-Yan contribution is estimated using MC simulated events normalized to the data at the $Z$ pole. By investigating the stability of the normalization factor a 4% systematic uncertainty is obtained on the SM Drell-Yan normalization. An uncertainty on the SM Drell-Yan shape due to PDF uncertainties is determined using the same method as used for the acceptance. The di-jet and $W$+jet backgrounds are treated as a single background, referred to as the jet background. The size of this background is estimated from a sample of jet events constructed from the data identically to the signal sample except that at least one electron candidate is not isolated and therefore likely to be a jet. From the distribution of the isolation of these ‘electron’ candidates, the number of jet events in the signal sample and its uncertainty is extracted. The shape of the jet background is estimated from a $J+Y$ sample, where $Y$ is either an electron or a jet misidentified as an electron. In the region where the jet background is significant, the normalization uncertainty is the dominant uncertainty on the jet background. Using these methods, the jet background is estimated to account for 0.8 ± 0.7% and 25 ± 8% of the total background above 150 GeV/$c^2$ in the CC and CP channels respectively. The remaining backgrounds are all estimated using MC simulation normalized to the theoretical next-to-leading order (NLO) or higher order cross section. The uncertainties in these background estimates are dominated by the 6% uncertainty on the luminosity.

A model-independent search for an excess over SM predictions is performed in an invariant mass range of $150 - 950$ GeV/$c^2$. The search is optimized for a narrow resonance, but still retains sensitivity to other signals which would produce an excess over SM predictions. Using 1 GeV/$c^2$ steps from $M_{ee} = 150$ to 950 GeV/$c^2$, the probability, referred to as the p-value, of observing at least as many events as recorded in the real experiment given the expected background rate is calculated using Poisson statistics in a mass window of $4.8 + 0.044 \times M_{ee}$ GeV/$c^2$. This mass window is approximately the width a narrow resonance would have if observed in the CDF detector, and this choice of mass window maximizes the sensitivity to discovering such a resonance for this particular analysis, as verified from studies of simulated events. The uncertainty on the background estimate is treated as a nuisance parameter with a Gaussian distribution. The p-values for the CC and CP channels are combined multiplicatively and the results are shown in Fig. 2. The minimum p-value expected in the absence of new physics depends on the size of the search range, with the expected minimum p-value decreasing as the search range increases. The range in which minimum p-value is expected to occur is shown in Fig. 2 and is defined to include 68.3% of the minimum p-values centered on the median value, using one million simulated mass spectra. Similarly, the 3σ evidence line is the p-value above which the minimum p-value in 99.85% of the simulated mass spectra fall; any p-value lower than this would be taken as evidence for the presence of new physics. The lowest p-value observed is at 367 GeV/$c^2$ and is within the expected range. It is therefore concluded that the results of this analysis are consistent with the SM.

To complement the above search, a Bayesian binned
likelihood method is used to extract limits on $\sigma \cdot B(X \rightarrow ee)$, where the mass of $X$ is within $\pm 10\%$ of its on-shell mass. As the acceptance of the final-state $ee$ system is required to extract a cross section, it is necessary to specify the spin of the particle. Both spin-1 and spin-2 particles are considered here. The likelihood is 1-dimensional with the signal cross section and is numerically integrated to obtain the limit on $\sigma \cdot B(X \rightarrow ee)$. The observed limits are shown in Fig. 3 for the spin-1 case. The $Z'$ model lines are obtained using the leading-order PYTHIA event generator [20] with a factor of 1.3 applied multiplicatively to account for NLO corrections.

In summary a search has been made for new physics in the $ee$ channel, and no significant excess over the standard model prediction is observed. Limits are placed on new spin-1 and spin-2 bosons. The SM-like $Z'$ is found to be excluded for masses below 923 GeV/$c^2$ and the $E_6$ $Z'$ bosons; the $Z'_1$, the $Z'_\psi$, the $Z'_{\chi}$, and the $Z'_\eta$ bosons are excluded with masses below 729, 822, 822, and 891 GeV/$c^2$ respectively. The direct limits presented here on all the $E_6$ $Z'$ bosons surpass the corresponding indirect limits from LEP [21]. The RS graviton with $k/M_{pl} = 0.1$ is excluded for masses below 807 GeV/$c^2$. When combined with the $\gamma\gamma$ channel, masses less than 889 GeV/$c^2$ are excluded for $k/M_{pl} = 0.1$. The above limits on $Z'$s and the RS graviton represent the best single–experiment direct limits to date.

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