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

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A search for a narrow resonance in di-electron events in the invariant mass range of $150 - 950$ GeV/c^2 is reported, using approximately 1.3 fb^{-1} of $p\overline{p}$ collision data collected by the CDF II detector at the Fermilab Tevatron at $\sqrt{s} = 1.96$ TeV. The search uses a frequentist p-value method to scan the mass spectrum for significant excesses over the Standard Model. Separately to the search, direct limits on $\sigma \cdot \mathrm{Br}(X \to ee)$ are placed on the Randall-Sundrum graviton and Z' bosons as a function of mass. The E_6 Z' bosons; the Z'_I, Z'_ψ, Z'_χ and Z'_η bosons are excluded with masses below 729, 822, 822, and 891 GeV/c^2 respectively. A Randall-Sundrum graviton with $k/\bar{M}_{pl} = 0.1$ is excluded for $M_G \leq 807$ GeV/c^2. These results are combined with the di-photon channel to improve the exclusion region for the Randall-Sundrum graviton to $M_G \leq 889$ GeV/c^2 for $k/\bar{M}_{pl} = 0.1$. These limits are the most exclusive limits at the current time.

Preliminary Results for Winter 2007 Conferences

I. INTRODUCTION

The standard model (SM) is incomplete. Many models which attempt to solve the problems of the unification of the fundamental forces and the hierarchy problem predict new particles coupling to di-electron (ee) pairs. This channel offers a relatively clean final state with low backgrounds at hadron colliders and thus has a strong discovery potential.

This note describes the search for new physics in high mass di-electron events from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, observed with the CDF II detector at the Fermilab Tevatron. The previous CDF search for new physics in this channel used an integrated luminosity of 448 pb^{-1} [1]. The analysis presented here uses an integrated luminosity that is larger by a factor of approximately three and also introduces a frequentist p-value based method to search the mass spectrum for any significant excesses above the Standard Model. The search is optimised for new physics processes which produce narrow ee resonances [2] but is otherwise model-independent. Separately to the search, limits are set using a Bayesian binned-likelihood method for specific models predicting additional neutral spin-1 and spin-2 bosons.

Grand Unification Theories (GUTs) unify the electroweak and strong forces, at some energy scale, into a larger gauge group. The breaking of the unified gauge group produces additional $U(1)$ symmetries, which manifest themselves as new massive neutral spin-1 bosons (Z') [3]. Additionally models have been proposed which solve the hierarchy problem posed by the large difference between the scales of the electroweak symmetry breaking and the Planck scale. One such model is the Randall-Sundrum (RS) [4] model of warped extra dimensions. This model introduces an extra dimension with a non-factorisable geometry which results in the prediction of a series of narrow neutral spin-2 resonances which decay into pairs of all SM particles. This analysis is sensitive to the first such resonance which is referred to in this note 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 $\bar{M}_{pl} = M_{pl}/\sqrt{8\pi}$ is the reduced effective Planck scale and k is the scale of warping in the extra dimension. The width of the RS graviton depends on $k/\bar{M}_{pl}$, with the width increasing with increasing $k/\bar{M}_{pl}$. The favored range of $k/\bar{M}_{pl}$ is from 0.01 to 0.1. The sensitivity of this analysis to the RS graviton is further improved by combining the results with a similar analysis of di-photon final states [5].

II. DATA SAMPLES & EVENT SELECTION

This analysis is based on an integrated luminosity of 1.3 fb^{-1} collected between March 2002 and September 2006 with the CDF II detector. The CDF detector is a general purpose particle 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 $|\eta| \leq 1.1$ [7]. The central and plug calorimeters are sampling calorimeters which surround the COT and consist of electromagnetic (EM) and hadronic sections and are used to measure the energy of particles in the range $|\eta| \leq 1.1$ and $1.2 \leq |\eta| \leq 3.6$ respectively.

The primary trigger used in this analysis requires two clusters of EM energy in the calorimeter. This trigger, together with two backup triggers, is 100% efficient for selecting events passing offline selection requirements. Events selected offline are required to have two electrons with $E_T \geq 25$ GeV. One electron is required to be incident in the central calorimeter ($|\eta| \leq 1.1$), with the other allowed to be incident in either the central calorimeter or the plug calorimeter ($1.2 \leq |\eta| \leq 3.0$). Electrons in the central calorimeter are required to have a well measured track while there is no tracking requirement for electrons in the plug. Electrons are identified in an identical way to the previously published analysis [1], with the exception that a photon conversion veto is applied to central electrons when the other electron is in the plug. This improves the sensitivity of the analysis by reducing the di-photon background in this channel. The main selection requirements are that the electrons be well isolated, have little hadronic energy and have a shower shape consistent with that of an electron. The selection cuts and search method were fixed before looking at the signal region of $M_{ee} \geq 150$ GeV/c^2 in data not included in [1].

The geometric and kinematic acceptance as a function of resonance mass is estimated using Monte Carlo (MC) samples. The PYTHIA event generator [8], with the CTEQ5L parton distribution functions (PDF) [9] and the CDF II detector simulation based on GEANT 3 [10], are used to generate all MC samples unless otherwise stated. A SM-like Z' is used for the 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 $\pm 10\%$ of their on-shell mass at generator level in order to cut out the low mass tail due to concerns over the accuracy of the MC simulation in this region. The uncertainty on the acceptance from the PDFs is estimated using the procedure recommended by the CTEQ Collaboration [11] and uses 40 different PDF sets, encapsulating the various uncertainties. The uncertainty on the acceptance due to initial state radiation (ISR) is estimated using PYTHIA to be 4%, by varying the parameters governing ISR. The electron identification efficiency, as a function of resonance mass, is estimated using the signal MC samples with data-derived corrections. A 2% systematic uncertainty on the identification efficiency at high mass is applied to reflect the lack of knowledge of the accuracy of the MC simulation at high electron energies.

III. STANDARD MODEL BACKGROUNDS

The most significant source of background to new physics in the di-electron channel is the SM Drell-Yan process via Z^0/γ^* and this represents an irreducible background. Di-jet events, where the jets are misidentified as electrons, represent the most significant reducible background. Other significant backgrounds are $W+Y$ events where $W \rightarrow e\nu_e$ and Y is a photon or a jet misidentified as an electron, and $\gamma\gamma$ events where the photons are misidentified as electrons. While other final states contribute to the background, they are not significant at high invariant masses. Fig. 1 shows the background estimates, together with the observed data for the central-central and central-plug channels combined.

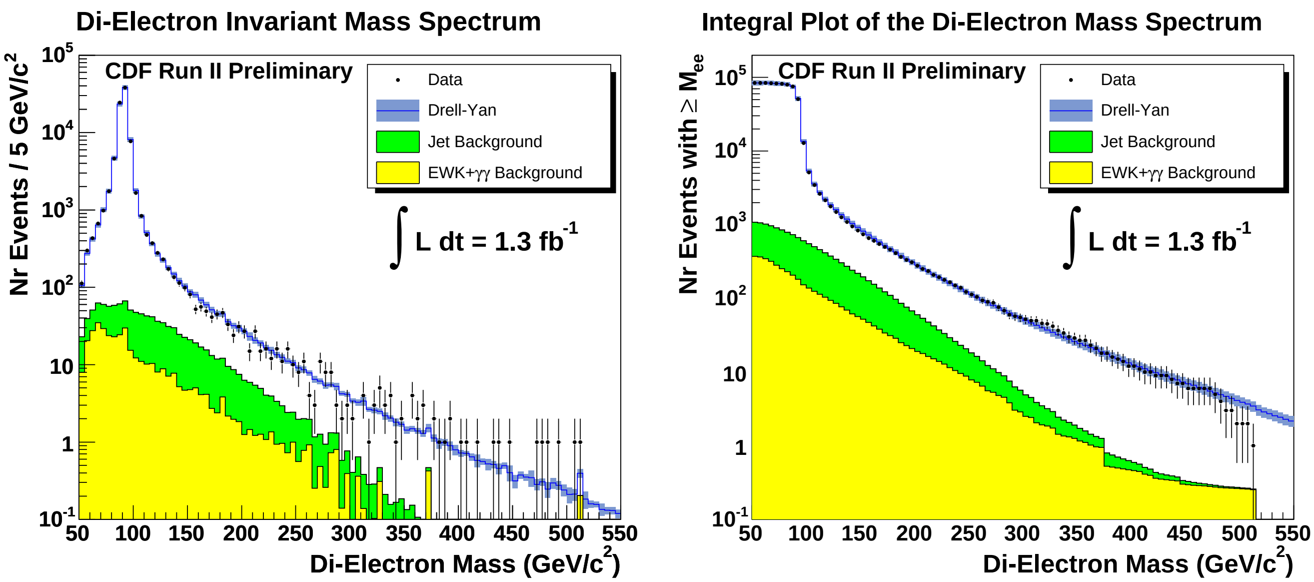

FIG. 1: The measured di-electron mass spectrum with the expected background in the central-central and central-plug channels combined. The plot on the right is the integral of this mass spectrum to better highlight any discrepancies from the background prediction. There are no observed events above 550 GeV/c^2.

The SM Drell-Yan contribution is estimated using MC simulated events normalized to the data in an invariant mass window of $76 \leq M_{ee} \leq 106$ GeV/c^2 for central-central events and $81 \leq M_{ee} \leq 101$ GeV/c^2 for central-plug events, with the difference in window size due to the increased jet background fraction in the central-plug channel. By comparing the normalization factors of the two channels, a 3.8% systematic uncertainity is obtained on the normalization of the SM Drell-Yan background. An uncertainity on the SM Drell-Yan shape due to PDF uncertainties is determined by re-weighting the Drell-Yan MC with the 40 different PDF sets in a similar manner to the case for the acceptance. The di-jet and $W + jet$ backgrounds are treated as a single background, referred to as the jet background. The normalization of the jet background is estimated by extrapolating from events where the electrons are not isolated. The uncertainty on the normalization is 78% and 29% in the central-central and central-plug channels respectively, with the uncertainty being obtained by varying the regions over which the extrapolation is made. As the jet background only accounts for 0.8% and 25% of the total background above 150 GeV/c^2 in the central-central and central-plug channels, this normalization uncertainity leads to only a 0.6% and 7.3% uncertainity on the total background in the two channels. The shape of the jet background is estimated from a $jet + Y$ sample, where Y is either an electron or a jet missidentified as an electron, with an uncertainity arising due to the E_T dependence of the probablility for a jet to be misidentifed as an electron. In the region where the jet background is significant, the normalization uncertainty is the dominant uncertainty on the jet background. The $\gamma\gamma$, $W + \gamma$, and remaining backgrounds are all estimated using MC simulation normalized to the theoretical cross section. The $W + \gamma$ sample is generated using the matrix element generator WGAMMA [12] and then subsequently processed using the PYTHIA event generator. The uncertainties in these background estimates are dominated by the 6% uncertainty on the luminosity [13].

IV. ANALYSIS INTERPRETATION

A. New Physics Search

A frequentist model independent search for an excess over SM predictions is performed on di-electron events 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 intervals from $M_{ee} = 150$ to 950 GeV/c^2, the probability for the background to fluctuate to the level observed in the data or higher, referred to as the p-value, 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 in pseudo-experiments. The uncertainty on the background estimate is treated as a nuisance parameter and it is integrated out assuming it is Gaussian distributed. The p-values for the central-central and central-plug channels are combined multiplicatively, and the results are shown in Fig. 2. The lowest p-value observed is at $M_{ee} \approx 367$ GeV/c^2, for which the background has a probability of 9.7×10^{-3} of fluctuating to the level of the data or higher. However, due to the large search range, there are many individual measurements which mean that it is increasingly likely to find large upward deviations from the background in the data by chance. To take this into account, the method is repeated for 50,000 pseudo-experiments produced using only the predicted background distribution as a template. This gives an expected range for the minimum p-value in the mass spectrum to lie, together with the p-value necessary to claim 3σ evidence of new physics, both of which are shown in Fig. 2. As the lowest observed p-value is within the expected range, it indicates that the excess at $M_{ee} \approx 367$ GeV/c^2 is consistent with a statistical fluctuation and therefore it is concluded that the results of this analysis are consistent with the SM.

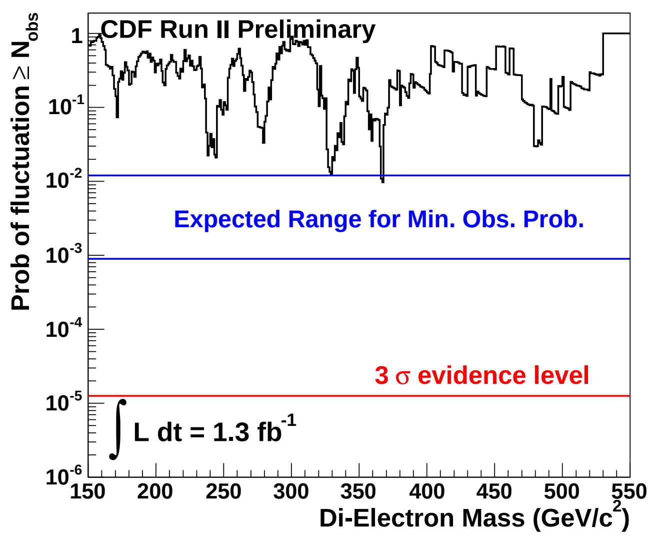

FIG. 2: The probability of the background to fluctuate to the level of the data or higher in a mass window equal to width of a narrow resonance in the CDF detector. The expected range is the range in which the minimum p-values of 68.3% of pseudo-experiments lie with the tails being symmetric. The 3σ evidence line corresponds to the p-value above which 99.7% of pseudo-experiments fall.

B. Limit Setting Technique

To compliment the the search, a Bayesian binned likelihood method is used to extract limits on $\sigma \cdot \mathrm{Br}(X \to ee)$ where the mass of X is within $\pm 10\%$ of its on-shell mass. As the acceptance of the particle is required to extract a cross section, unlike for the search it is nescessary to specify the spin of the particle. This note considers both spin-1 and spin-2 particles. The likelihood is a 1-dimensional likelihood with the signal cross section as the free parameter and the bin contents treated using Poisson statistics. The likelihood is then convoluted with a Gaussian to take into account the uncertainty on the cross section from the acceptance, background and luminosity estimates. The probability density function is formed by taking a flat prior for the signal cross-section and is numerically integrated

k/M_{pl}	0.01	0.025	0.05	0.07	0.1
ee	302	469	674	741	807
$\gamma\gamma$	230	496	695	782	850
$ee+\gamma\gamma$	267	580	761	820	889

TABLE I: RS graviton mass limits in units of GeV/c^2 for various values of $k/\bar{M}_{pl}$ at the 95% confidence level.

to obtain the 95% CL limit on $\sigma \cdot \mathrm{Br}(X \to ee)$. To translate an uncertainity on an input quantity, such as the expected background or luminosity, to an uncertainity on the extracted cross section, pseudo-experiments are generated using the fluctuated background distribution as a template are generated with a signal of known cross section present. The signal cross section is then extracted using the nominal background template and the mean of the difference between the input and extracted cross sections is taken to be the cross section uncertainty. This is done for several signal cross sections to obtain the cross section uncertainty as a function of the cross section. The observed limits are shown in Fig. 3 for two cases. The Z' model lines are obtained using the PYTHIA event generator using the couplings in [14], while the RS graviton model lines are obtained using the HERWIG event generator [15]. A K-factor of 1.3 to account for next-to-leading order corrections.

For the specific case of the RS graviton, which has a branching ratio to di-photons twice that of di-electrons, the analysis sensitivity can be improved by combining with the di-photon channel described in [5]. Di-Photon events are required to have two photons, both with $E_T \geq 15$ GeV, with one in the central calorimeter ($|\eta| \leq 1.04$) and the other either in the central or plug calorimeters ($1.2 \leq |\eta| \leq 2.8$). The central-central and central-plug channels use integrated luminosities of 1.2 fb^{-1} and 1.1 fb^{-1} respectively, with the difference arising from the requirement that the silicon system be operational for events in the central-plug channel. Selected photons have similar isolation and shower shape requirements to electrons, however photons are required not to have an associated track, which ensures zero overlap between the di-photon and di-electron sample.

The di-photon channel is combined with the di-electron channel by multiplying the likelihoods together. The uncertainties on the background estimates are taken to be uncorrelated. The errors on the acceptance and luminosity are taken to be 100% correlated. The combined limits together with the $k/\bar{M}_{pl}$ vs graviton mass exclusion region are shown in Fig. 4. The excluded RS graviton masses are summarised in table I.

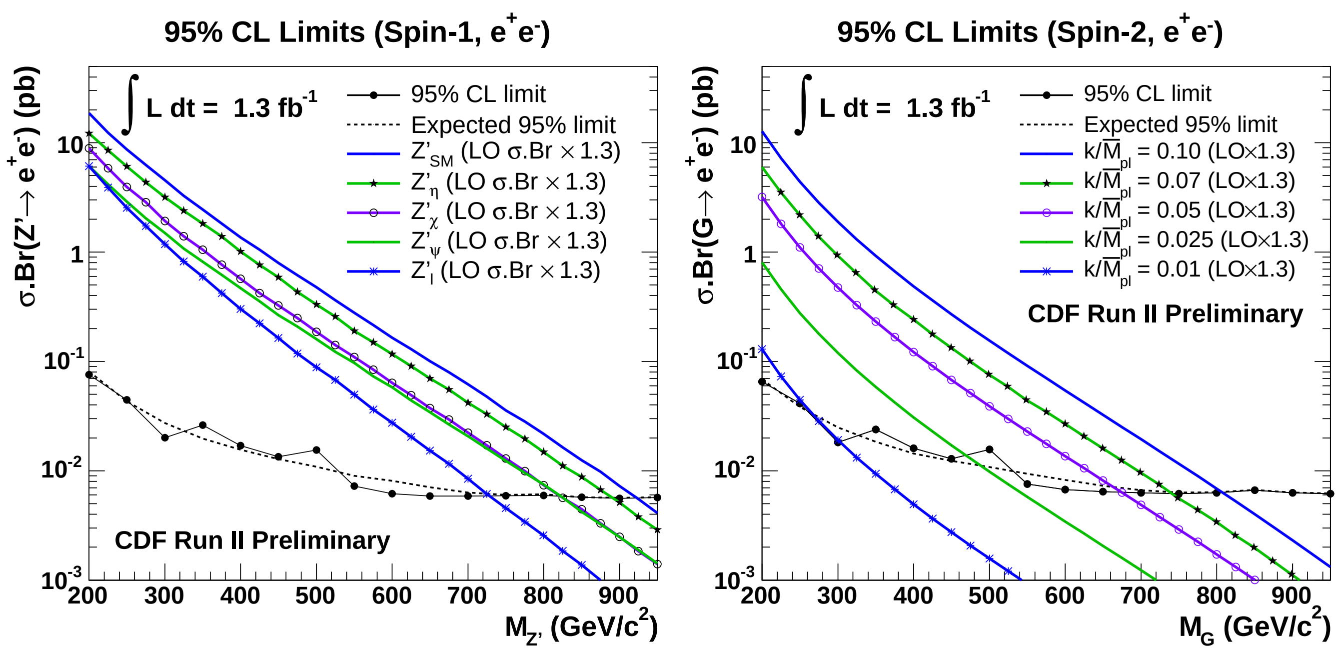

FIG. 3: The 95% confidence level limits on $\sigma.Br$ for a neutral spin-1 boson (left) and spin-2 boson (right).

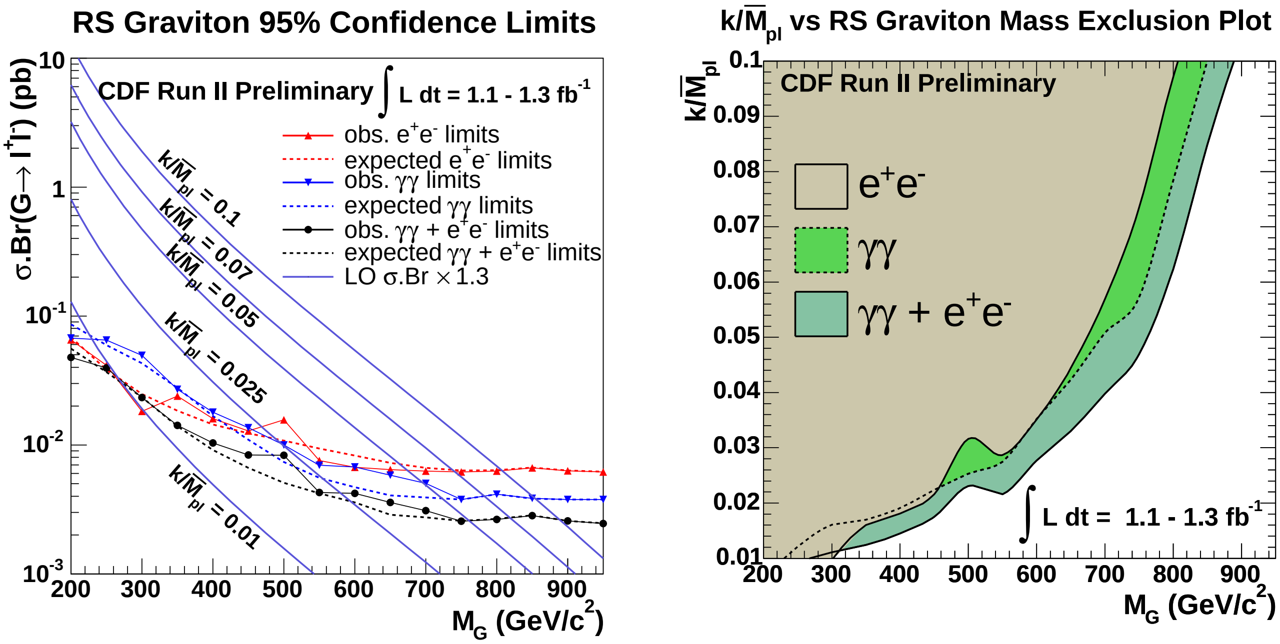

FIG. 4: The 95% confidence level limits on $\sigma \cdot \mathrm{Br}(G \rightarrow ee)$ (left) and $k/\bar{M}_{pl}$ (right) for a RS graviton in the di-electron, di-photon channels seperately and combined.

V. SYSTEMATIC UNCERTAINTIES

The main sources of systematic uncertainties effecting this analysis have been discussed in the text but are listed below for clarity. The uncertainties are either direct uncertainties on the signal cross-section, such as the luminosity error, or on the background expectation such as the SM Drell-Yan normalisations. Uncertainties on the signal cross section only effect the limits while uncertainties on the background estimate effect both the search and the limits. The background uncertainty dominates the total uncertainty for the limits in the low mass region ($M_{ee} \leq 400$), while the uncertainties on the signal cross0section dominate the high mass region.

- **Systematic Uncertainty from Energy Scale and Resolution**
  The energy scales of the central and plug calorimeters in the MC simulation are varied separately by $\pm 1\%$. The energy of the MC events is also seperately smeared by an additional 0.7% in the central calorimeter and 0.5% in the plug calorimeter to account for the resolution errors.

- **Parton Distribution Functions (PDF) Uncertainty**
  The relative change in the background template and signal acceptance due to PDF uncertainties is found by re-weighting MC events with each of the 40 PDF sets obtained by varying the 20 eigenvectors which make up the CTEQ6M PDF $\pm 1\sigma$ and comparing to the results obtained by the nominal CTE6QM PDF.

- **Uncertainties on the Background Expectations**
  The uncertainty on the SM Drell-Yan normalisation is determined to be 3.8%. The di-jet background has an 78% normalisation uncertainty in the central-central channel and a 29% error in the central-plug channel. This normalisation error is obtained from the statisical uncertainty on the method combined in quadrature with the systematic uncertainty obtained from varying the parameters of the method. An uncertainty on the shape is obtained by investigating the E_T dependence of the probability for a jet to fake an electron. Other backgrounds are suffiently small so that any uncertainity on them has an insignificant effect on the total background uncertainity.

- **Initial State Radiation (ISR)**
  The parameters in the Monte Carlo simulation related to the ISR calculation were changed to be half and then double the default values. This study resulted in a 4% uncertainity being applied to the acceptance due to the ISR uncertainity.

- **Luminosity**
  The uncertainty on the luminosity is 6% resulting in a 6% uncertainity on the extracted cross-section limits.

- **Electron ID Efficiency**
  The uncertainty on the electron ID efficiency is 2% resulting in a 2% uncertaniity on the extracted cross-section limits.

VI. RESULTS

This analysis has searched for new physics in the di-electron 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 at 95% confidence level for masses below 923 GeV/c^2 and the E_6 Z' bosons, the Z'_I, the Z'_ψ, the Z'_χ, and the Z'_η bosons, are excluded at the 95% confidence level with masses below 729, 822, 822, and 891 GeV/c^2 respectively. For the first time post LEP, the limits on all the E_6 Z' bosons exclude the indirect limits from precision electroweak measurements [16]. The RS graviton with $k/\bar{M}_{pl} = 0.1$ is excluded at 95% confidence level for masses below 807 GeV/c^2. When combined with the di-photon channel, the excluded masses become 889 GeV/c^2 for $k/\bar{M}_{pl} = 0.1$. These represent the worlds best single experiment direct limits to date.

Acknowledgments

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