CDF Note 10405

Search for New Dielectron Resonances and Randall-Sundrum Gravitons at the Collider Detector at Fermilab

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(http://www-cdf.fnal.gov)

February 14, 2011

Abstract

A search for new dielectron mass resonances using 5.7 fb^{-1} of data recorded by the CDF II detector is presented. No significant excess over the expected standard model prediction is observed. In this dataset, an event with the highest dielectron mass ever observed (960 GeV/c^2) is recorded. The results are intepreted in the Randall-Sundrum (RS) model. Combined with the 5.4 fb^{-1} diphoton analysis, the RS-graviton mass limit for the coupling $k/\overline{M}_{Pl} = 0.1$ is 1055 GeV/c^2 making it the strongest limit to date.

I. INTRODUCTION

Although extremely successful, the standard model (SM) of particles and fields is not sufficient for solving many open physics problems including the origin of the dark matter, the incorporation of gravity, and the weak-scale/Planck-scale hierarchy problem. Many extensions of the SM have been proposed, most of which predict the existence of new particles. The most direct way of discovering a new unstable particle is through a mass resonance of its decay products. In this note we present a search for high-mass dielectron resonances.

At hadron colliders, the search for dilepton high-mass resonances has the benefit of very low hadronic backgrounds and well-understood electroweak backgrounds. The search for dielectron resonances is motivated by the event-yield excess at a dielectron mass $M_{ee} = 240$ GeV/c^2 reported by a 2.3 fb^{-1} CDF analysis [1]. Moreover, a recent CDF search [2] for Randall-Sundrum (RS) gravitons decaying to diphotons will significantly benefit from the addition of the dielectron-decay channel. The RS model [3] solves the hierarchy problem by introducing an extra compact dimension accessible only to gravity. The phenomenology leads to a small number of distinct Kaluza-Klein states (spin-2 gravitons G) that couple to SM particles and can be individually detected as resonances of pairs of jets, leptons, photons or gauge bosons. Other possible sources of dielectron resonances include the production of heavy gauge bosons (Z') and spin-0 particles (such as the Higgs boson and supersymmetric particles).

In this note we first present a model-independent search for dielectron resonances and we subsequently use the results to exclude part of the RS-graviton parameter space. The dielectron search is combined with the recent CDF diphoton RS-graviton search to set the strongest limit to date. Searches for dielectron resonances with RS-graviton interpretation have been previously published by the CDF [1] and D0 [4] collaborations.

II. THE CDF II DETECTOR

The CDF II detector [5] is a multi-purpose cylindrical detector with projective-tower calorimeter geometry and excellent lepton identification capability. It operates at the Tevatron collider at Fermilab where protons and antiprotons collide with a center-of-mass energy of 1.96 TeV. In our coordinate system the positive $\vec{z}$-axis is defined by the proton beam direction and the positive $\vec{y}$-axis by the vertical upward direction. The detector is approximately symmetric in the η and ϕ directions, where the pseudorapidity η is defined as $\eta = -\ln(\tan(\theta/2))$, θ is the polar angle with respect to $\vec{z}$, and ϕ is the azimuthal angle.

The momentum p of charged particles is measured by a tracking system composed of an eight-layer silicon strip detector and a 96-layer drift chamber; both are located inside a solenoid providing a magnetic field of 1.4 Tesla aligned along the beam axis. The tracking efficiency is nearly 100% in the "central" region ($|\eta| < 1$) and decreases in the forward region ($2.8 > |\eta| > 1$). Electromagnetic and hadronic calorimeters surround the solenoid and measure the energies of collision products up to $|\eta| = 3.6$. The relative energy resolution is $13.5\%/\sqrt{E_T} \oplus 2\%$ for the central electromagnetic and $75\%/\sqrt{E_T} \oplus 3\%$ for the central hadronic calorimeter, where the transverse energy $E_T = E \sin\theta$ is quoted in GeV units. Gas Cherenkov counters measure the average number of inelastic $p\bar{p}$ collisions per bunch crossing and thereby determine the beam luminosity. A pipelined three-level trigger system [6] that combines hardware and software is used for filtering the collision data.

III. DATA SELECTION

We perform an analysis of CDF dielectron data collected with a high-transverse momentum ($p_T \equiv p \sin\theta > 18$ GeV/c) central electron trigger and corresponding to an integrated luminosity of 5.7 fb^{-1}. To ensure a uniform trigger response, we require the central electron to have $p_T > 20$ GeV/c. A complementary, less stringent trigger especially for electrons with $p_T > 70$ GeV/c is also used. The second electron can pass either through the central or forward detector region and it is required to have p_T greater than 5 GeV/c. The tracking system provides the direction of the electrons, whereas the absolute value of their 3-momentum is determined from the energy deposited in the calorimeters. This energy is required to geometrically match the track and be consistent with that expected from electrons. The excess transverse calorimeter energy deposited in a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ around each electron must be less than 10% of its transverse energy. The electrons are required to be $\Delta R > 0.4$ away from each-other and to have the z coordinate of their tracks at the origin within $|\Delta z| < 5$ cm. The average z position of the two tracks must be within 4 cm of an interaction vertex. Finally, each electron must have a track with an impact parameter less than 0.02 cm, if the track is reconstructed including information from the silicon detector, or less than 0.2 cm otherwise. The forward electrons can also be linked to special silicon-only tracks, due to the limitation of the drift tracker η coverage. No opposite-charge requirement is imposed.

IV. SM BACKGROUNDS

The main dielectron SM background is the Drell-Yan (DY) process $q\bar{q} \rightarrow Z/\gamma^* \rightarrow e^+e^-$. Secondary electroweak backgrounds come from diboson production (WW, WZ, ZZ, $W\gamma^*$) with subsequent electronic decays. The main hadronic background contributing to the dielectron candidate sample is the production of W+jets, where the W boson decays to an electron and the jet is misidentified as an electron ("fake" electron). Finally, the $t\bar{t}$ decays to dielectrons are also considered.

The DY, diboson, and $t\bar{t}$ backgrounds are estimated with Monte Carlo (MC) simulation, using PYTHIA [7], running with the CTEQ5L [8] parton distribution functions, and the CDF GEANT-based [9] detector simulator. The MC events are normalized on event-by-event basis based on the theoretical next-to-leading-order cross sections, event trigger efficiencies, electron identification scale factors and data luminosity. The good agreement between SM expectation and CDF data in the Z resonance validates our DY prediction. The diboson background estimation is validated in a trilepton control region with $\not\!\!E_T > 15$ [10], where the diboson contribution is significant. The $t\bar{t}$ dielectron background is validated in a control region with two or more hadronic jets, $H_T > 200$ GeV [11], and $\not\!\!E_T > 20$, where the top-quark pair production is the dominant process.

The hadronic QCD background is estimated using CDF data, by selecting events with an identified electron and applying to every well-reconstructed and fiducial jet a probability to be misidentified as an electron. The probability for a jet to fake an electron is determined from jet-rich CDF data [12]. The QCD background measurement is validated in the intermediate-mass ($20 < M_{ee} < 76$ GeV/c^2) control region, as well as in the trilepton ($76 < M_{ee} < 106$ GeV/c^2) and high-mass $t\bar{t}$ control regions described above.

TABLE I: Sources of systematic uncertainties and their effect on MC-estimated and data-measured backgrounds.

Systematic source	Effect	MC or data
Luminosity	6%	MC
Lepton-ID efficiency	2%	MC
Trigger efficiency	0.5%	MC
Parton distribution functions	1-2%	MC
Theoretical cross sections	7-8 %	MC
Fake probability	50 %	data

V. SYSTEMATIC UNCERTAINTIES

The main sources of MC-related systematic uncertainties are summarized in Table I. The total MC systematic uncertainty is ~ 10 %. The QCD-background systematic uncertainty is ~ 50 %, which comes from the variation in the measurement of the fake probabilities using jet-rich CDF datasets triggered by different jet energies. The total systematic uncertainty depends on the fraction of the background due to each source, which varies with the M_{ee} bin, and results to a 10 - 15 % total systematic uncertainty. Since the SM background is very low in the dielectron-mass region of interest, the results are not overly sensitive to the systematic uncertainties.

VI. SEARCH FOR NEW DIELECTRON RESONANCES

Fig. 1 shows the M_{ee} spectrum for SM expectation and CDF data. We observe good agreement in the Z-boson resonance, which validates our efficiencies, scale-factors, data luminosity and theoretical cross sections. We also observe the mass tail coming from electroweak and hadronic sources. Fig. 1 also shows the M_{ee} spectrum between 200 and 600 GeV/c^2. We observe good agreement in that region and the previously reported excess of events at 240 GeV/c^2 has been reduced to a 1.7 σ effect with this larger dataset. We also observe an exceptional $M_{ee} = 960$ GeV/c^2 event, the highest-mass dielectron ever observed. Calorimeter resolution induces an uncertainty on the dielectron mass of 16 GeV/c^2. The two electrons have transverse momenta of 482 and 468 GeV/c, they originate from the same primary vertex and are oppositely charged. The event is characterized by very low hadronic activity (no jets are reconstructed) and by a missing transverse energy of 17 GeV, separated

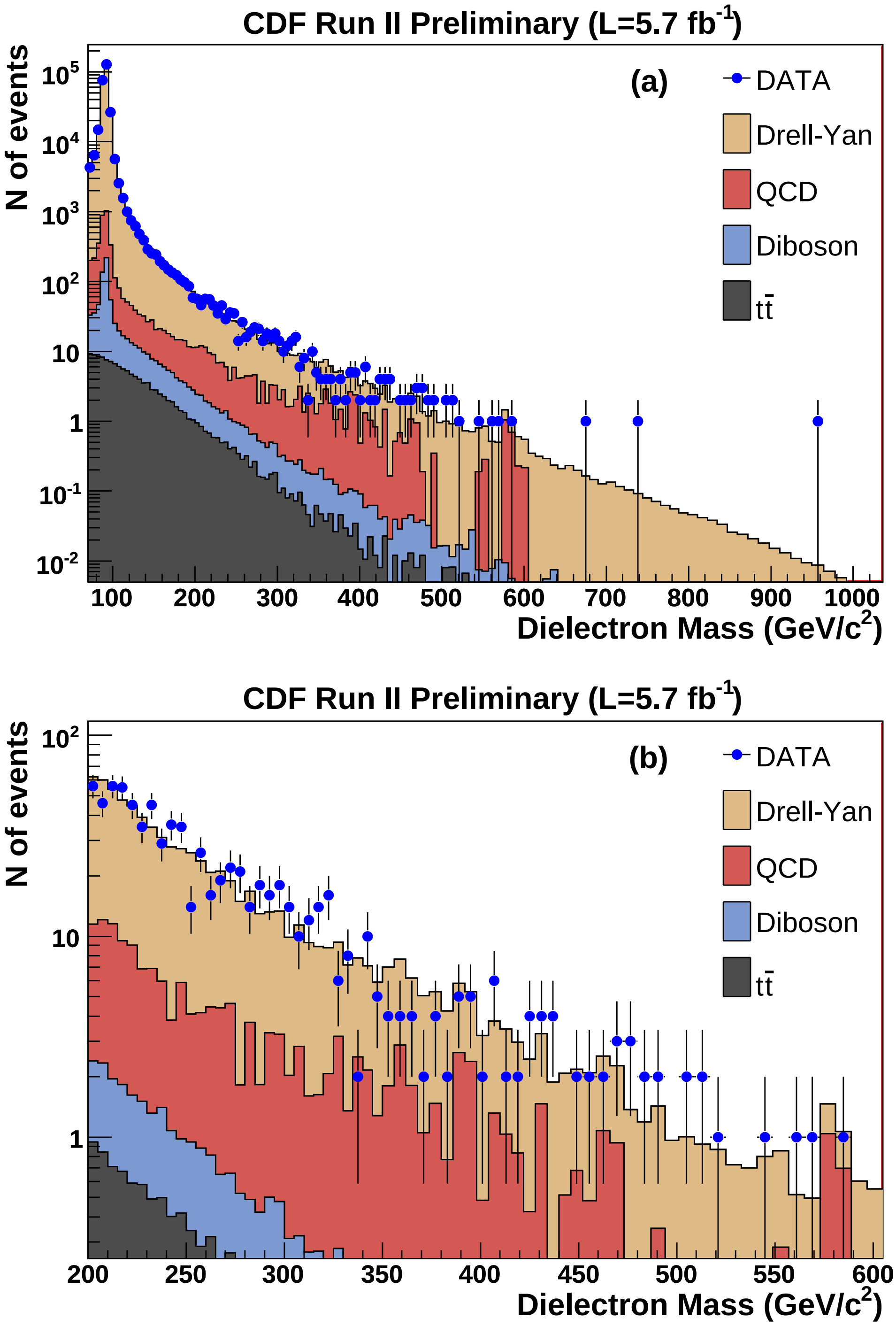

FIG. 1: (a) The dielectron mass distribution for the SM background (stacked histograms of DY, electron+fake, diboson, and $t\bar{t}$) and the CDF data of 5.7 fb^{-1}. The QCD background (lepton+fake) is measured from CDF data. The electroweak backgrounds are estimated using MC normalized to the data luminosity and theoretical cross sections, without fitting to any part of the dielectron data distribution. (b) The dielectron mass distribution between 200 and 600 GeV/c^2.

by 23 degrees in ϕ from the 468 GeV/c electron, coming most probably from the resolution of the calorimeter.

In order to assess the agreement between SM and observation, for every mass bin i we define a p-value as the probability to observe at least N^i_{data} events, when N^i_{SM} events are expected. We determine this probability by generating pseudoexperiments and counting the fraction of the time when $N^i_{pseudo} \geq N^i_{data}$, where the N^i_{pseudo} follows a Poisson distribution with a mean which itself follows a Gaussian distribution with a mean equal to N^i_{SM} and standard deviation equal to the SM systematic uncertainty for the ith bin. Fig. 2 shows the p-value as a function of the M_{ee}. The red lines define the 1-σ expected range of the minimum p-value that could be observed in any mass bin. This range is calculated from the probability distribution of minimum p-values determined with the use of pseudoexperiments. The probability to observe a SM event with $M_{ee} \geq 960$ GeV/c^2 is 4%. The second most significant excess of events is observed at $\sim$320 GeV/c^2.

VII. LIMITS ON RS-GRAVITON PRODUCTION

The measured M_{ee} spectrum can be used to set a limit on RS-graviton production. Here we parametrize the RS model using the mass of the lightest RS graviton (m_1) and the dimensionless parameter $\sqrt{8\pi}k/M_{Pl} \equiv k/\overline{M}_{Pl}$, where k is the curvature scale of the extra dimension and M_{PL} is the Planck mass. RS-graviton signal MC is generated using PYTHIA and values of m_1 from 200 to 1100 GeV/c^2. The signal-MC events are normalized in the same manner as the background-MC ones. The CDF acceptance for the dielectron RS-graviton signal, as determined using MC, is 27% and approximately independent of the RS-graviton mass, due to the use of forward electrons. The RS-graviton decays to two jets (branching ratio Br=70%), two charged leptons (Br=6%), two neutrinos (Br=6%), two photons (Br=4%) and two weak bosons (Br=14%). Given the considerable dijet background in a hadron-collider environment, and the low leptonic branching fraction of the weak bosons, the prompt dilepton and diphoton final states offer the greatest sensitivity. The inclusion of dielectrons in the diphoton RS search [2] offers a 50% increase in the rate of potentially produced signal. Here we present the cross section and mass limits for dielectrons and the dielectron+diphoton combination.

Fig. 3 shows the 95% confidence level (CL) cross-section ($\sigma \times \mathrm{Br}(G \rightarrow ee)$) exclusion

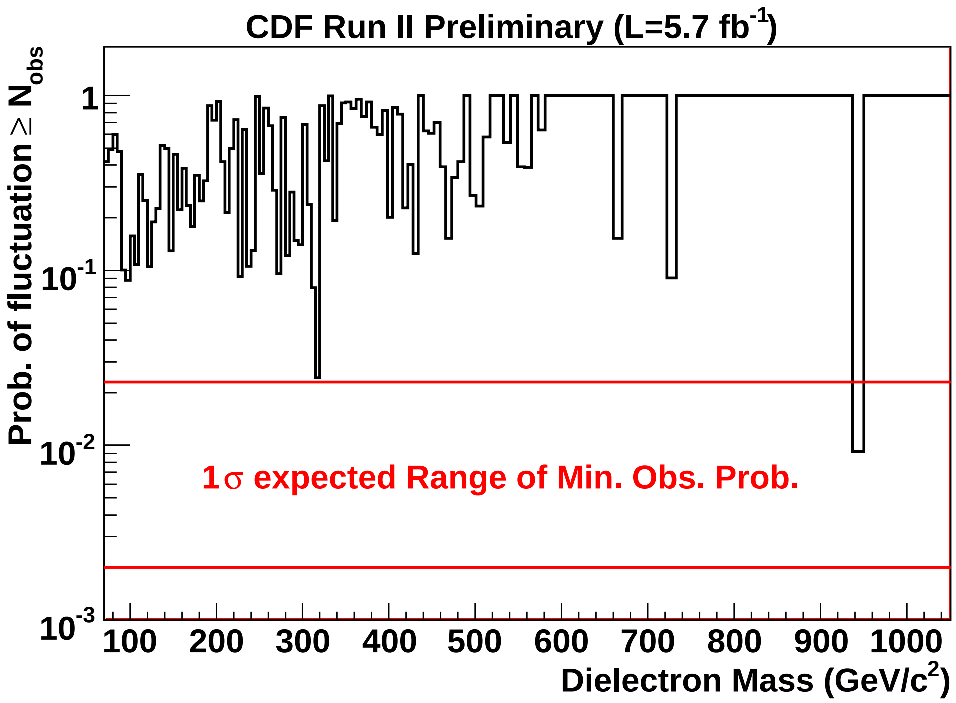

FIG. 2: The p-value as a function of the dielectron mass.

limit as a function of the lightest RS-graviton mass m_1 along with five theoretical cross-section curves for $k/\overline{M}_{Pl} = 0.01$ to 0.1, a theoretically interesting range that would solve the fine-tuning problem. The limits are set using a frequentist method that compares the background-only with the signal+background hypotheses [2, 13]. The intersection of the cross-section exclusion limit with the theoretical cross-section curves gives the 95% CL limit on m_1 for the respective coupling. For $k/\overline{M}_{Pl} = 0.1$, the dielectron-only m_1 limit is 907 GeV/c^2, if we use proper mass-dependent RS-graviton K-factors [14–18], and 927 GeV/c^2 assuming a fixed K-factor of 1.54 [4], for comparison with previous results [1, 4]. For $m_1 > 700$ GeV/c^2, the dielectron-only analysis excludes cross sections greater than 2 fb at the 95% CL. Fig. 3 also shows the 95% CL cross-section ($\sigma \times \mathrm{Br}(G \to ee/\gamma\gamma)$) exclusion limit from the combination of the dielectron and diphoton analyses. The two analyses are combined as independent channels bound by a common production cross section [13]. For $k/\overline{M}_{Pl} = 0.1$, the combined m_1 limit is 1055 GeV/c^2, if we use proper mass-dependent RS-graviton K-factors, and 1089 GeV/c^2 assuming a fixed k-factor of 1.54. For $m_1 > 700$ GeV/c^2, the combined $ee + \gamma\gamma$ analysis excludes cross sections greater than 0.9 fb at the 95% CL.

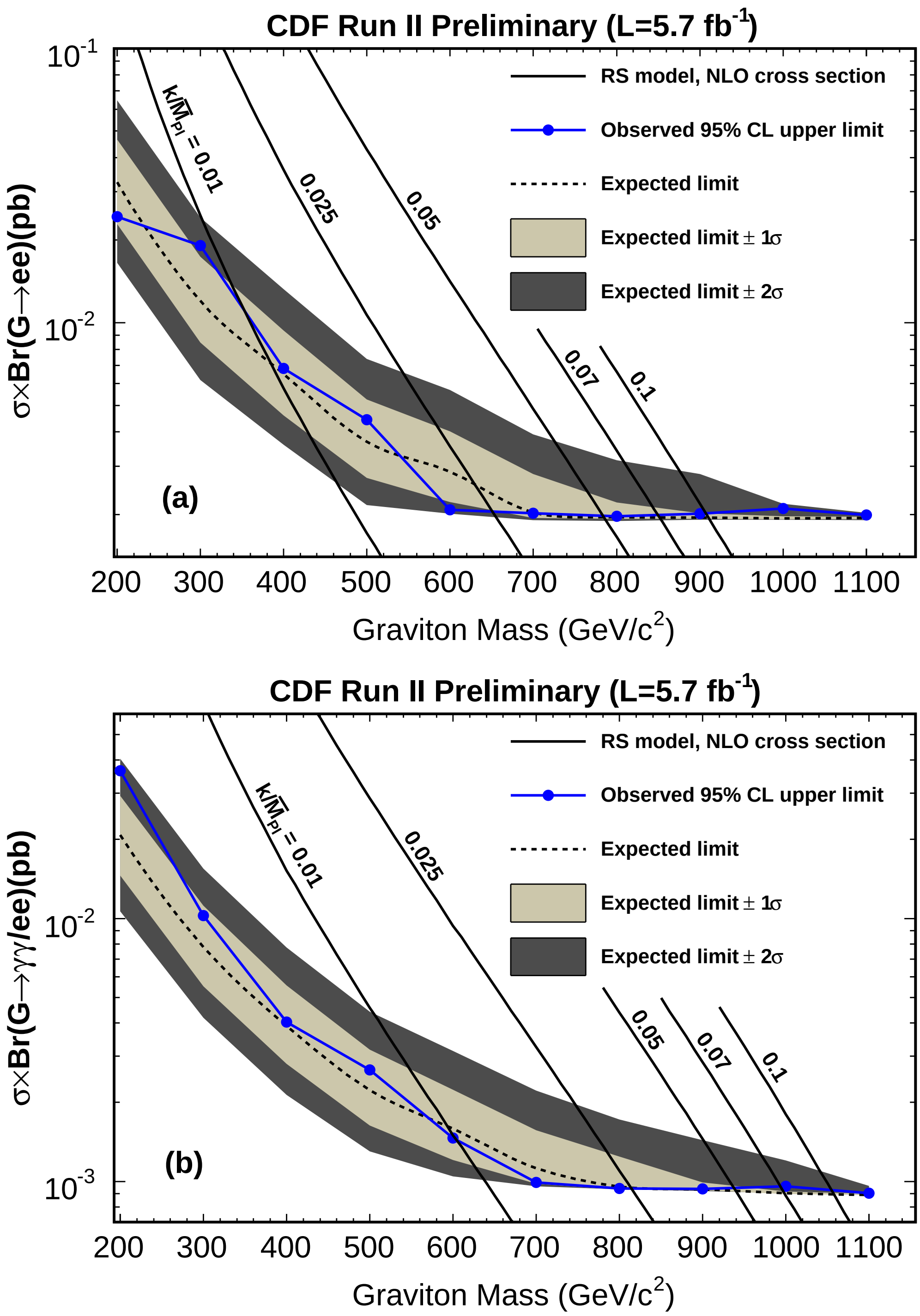

FIG. 3: (a) The upper 95% CL limit on the lightest RS-graviton production cross section from the dielectron analysis, as a function of the graviton's mass. Five theoretical curves are shown for five values of the coupling $k/\overline{M}_{Pl}$ from 0.01 to 0.1. The intersections give the RS-graviton mass limits for the five hypotheses. (b) The respective cross section and mass limits for the combination of the dielectron and diphoton analyses. The inclusion of the dielectron analysis improves the $k/\overline{M}_{Pl} = 0.1$ limit by $\sim$95 GeV/c^2.

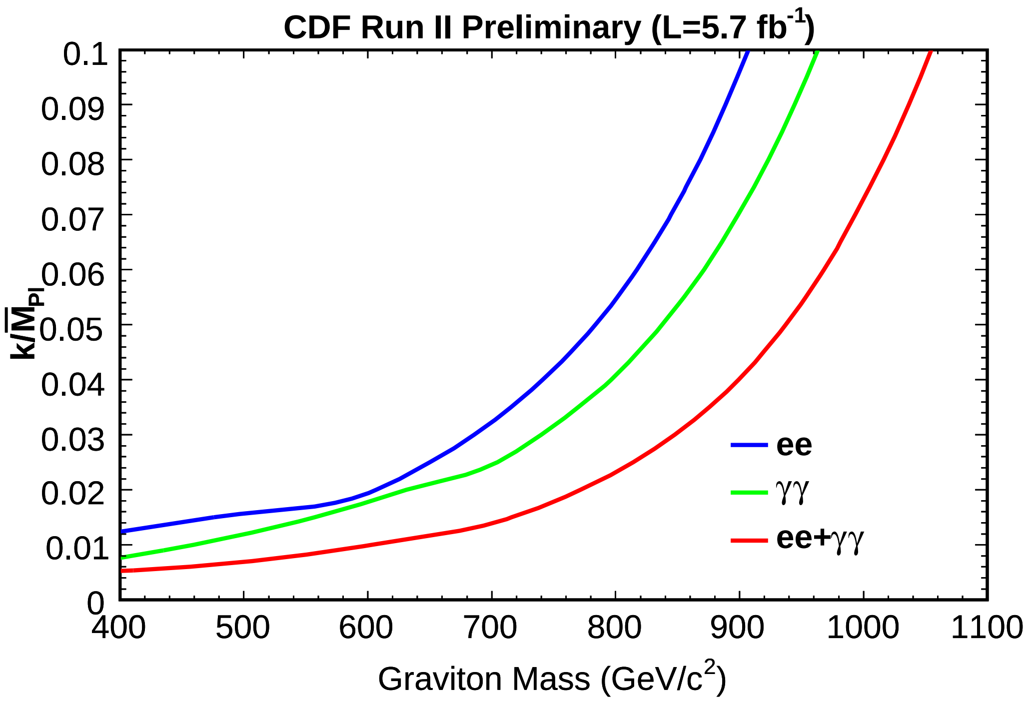

FIG. 4: The area excluded in the $k/\overline{M}_{Pl}$ vs. m_1 parameter space by the dielectron analysis, diphoton analysis, and their combination.

TABLE II: The 95% CL RS-graviton mass limits from the combined $ee+\gamma\gamma$ analysis, for five values of $k/\overline{M}_{Pl}$.

$k/\overline{M}_{Pl}$	Mass limit (GeV/c^2)
0.01	604
0.025	814
0.05	937
0.07	994
0.1	1055

Fig. 4 shows the exclusions in the $k/\overline{M}_{Pl}$ vs. m_1 parameter space for the dielectron analysis, the diphoton analysis and their combination. Overall, the inclusion of electrons improves the previous CDF RS-graviton limit by ∼95 GeV/c^2 and the current D0 limit by ∼40 GeV/c^2. Table II summarizes the combined $ee + \gamma\gamma$ RS-graviton mass limits for different values of $k/\overline{M}_{Pl}$.

VIII. CONCLUSIONS

In summary, we present a search for high-mass dielectron resonances using 5.7 fb^{-1} of CDF data. We do not observe any significant discrepancies from the expected SM prediction, while we detect the highest-mass dielectron event ever observed, at 960 GeV/c^2. We use the dielectron mass spectrum to set 95% CL limits on the RS-graviton production, for several values of the $k/\overline{M}_{Pl}$ parameter. The limit from the combined dielectron and diphoton analyses and for $k/\overline{M}_{Pl} = 0.1$ is 1055 or 1089 GeV/c^2, depending on the assumption on the NLO cross sections, making this result the most stringent to date.

IX. ACKNOWLEDGMENTS

We thank V. Ravindran, P. Mathews and M. C. Kumar for the calculation of the mass-dependent RS-graviton K-factors. We also thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

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