CDF Note 10405

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

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Abstract

A search for new dielectron mass resonances using data recorded by the CDF II detector and corresponding to an integrated luminosity of 5.7 fb^{-1} 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) was recorded. The results are interpreted 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 1058 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 answering many open physics questions including the origin of the dark matter, the incorporation of gravity, and the weak-scale/Planck-scale hierarchy. Many extensions of the SM have been proposed, most of which predict the existence of new particles. The most direct way to discover a new unstable particle is through a mass resonance of its decay products. In this Letter we present a search for high-mass dielectron resonances.

At hadron colliders, the search for high-mass dilepton resonances has the advantage of very low hadronic backgrounds and well-understood electroweak backgrounds. The search for dielectron resonances is motivated by the event excess at a dielectron mass M_{ee} = 240 GeV/c^2 reported by a CDF analysis [1] performed with an integrated luminosity of 2.3 fb^{-1}. Moreover, a recent CDF search [2] for Randall-Sundrum (RS) gravitons decaying to diphotons will benefit significantly 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 of this model 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 spin-1 (e.g., Z' [4]) and spin-0 particles (e.g., Higgs boson [5] and supersymmetric particles [6]).

In this Letter 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 limits to date. Searches for dielectron resonances with RS-graviton interpretation have been previously published by the CDF [1] and D0 [7] collaborations.

II. THE CDF II DETECTOR

CDF II [8] is a multi-purpose cylindrical detector with projective-tower calorimeter geometry and excellent lepton identification capability. It operates at Fermilab's Tevatron collider where protons and antiprotons collide with a center-of-mass energy of 1.96 TeV. In CDF's 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 with 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 T aligned along the beam axis. The tracking efficiency is nearly 100% in the central region ($|\eta| < 1$) and decreases in the forward region ($1 < |\eta| < 2.8$). Electromagnetic and hadronic calorimeters surround the solenoid and measure the energies of collision products up to $|\eta| = 3.6$. 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 [9] 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 supplementary trigger, more efficient 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 $p_T > 5$ 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 additional 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 separated by $\Delta R > 0.4$ 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 be linked to special silicon-only tracks in order to extend the reach in η beyond that of the drift chamber coverage. Due to the limitation in determining the charge of forward electrons, no opposite-charge requirement is imposed. After the above selection, we retain 240,224 dielectrons in the Z-boson resonance ($76 < M_{ee} < 106$ GeV/c^2) and 801 dielectrons with $M_{ee} > 200$ GeV/c^2.

IV. SM BACKGROUNDS

The main SM dielectron background to a high-mass dielectron signal is the Drell-Yan (DY) process $q\bar{q} \to Z/\gamma^* \to e^+e^-$. 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, $t\bar{t}$ events decaying to dielectrons are also considered.

The DY, diboson, and $t\bar{t}$ backgrounds are estimated with Monte Carlo (MC) simulation, using PYTHIA [10], running with the CTEQ5L [11] parton distribution functions, and the CDF GEANT-based [12] detector simulator. The MC events are normalized on an event-by-event basis using the theoretical next-to-leading-order cross sections [13], event trigger efficiencies, electron identification scale factors and data luminosity. Good agreement between SM expectation and CDF data in the Z resonance will validate our DY prediction. The diboson background estimation is validated in a trilepton $ee + e/\mu$ control region with $\not\!\!E_T > 15$ GeV [14], 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 [15], and $\not\!\!E_T > 20$ GeV, 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 [16]. The QCD background estimation 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.

V. SYSTEMATIC UNCERTAINTIES

The main sources of systematic uncertainty on the MC-estimated backgrounds [17] are the theoretical cross sections (an 8% effect on the event yields), the luminosity (6%), the lepton-ID efficiency (2%), the parton distrubition functions (2%), and the trigger efficiency (0.5%). The total MC systematic uncertainty on the expected event yield is $\sim$ 10 %. The respective QCD-background systematic uncertainty is $\sim$ 50 %, which comes from the variation in the measurement of the fake probabilities using different jet-rich CDF datasets triggered with varied jet-energy thresholds. Since the SM background is very low in the high dielectron-mass region of interest, the results are not overly sensitive to the systematic uncertainties.

VI. SEARCH FOR NEW DIELECTRON RESONANCES

Figure 1(a) shows the M_{ee} spectrum for SM expectation and CDF data. We observe good agreement in the Z-boson resonance region, which validates our efficiencies, scale factors, data luminosity and theoretical cross sections. We observe a long mass tail coming mainly from the DY process. Figure 1(b) shows the M_{ee} spectrum between 200 and 600 GeV/c^2; above 200 GeV/c^2, we expect 793 ± 96 events and observe 801. We observe an exceptional $M_{ee} = 960$ GeV/c^2 candidate event, the highest-mass dielectron event ever observed. Calorimeter resolution induces an uncertainty on the dielectron mass of 16 GeV/c^2 for this event. 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 low missing transverse energy of 17 GeV – separated 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 number of times when $N^i_{pseudo} \geq N^i_{data}$. Here N^i_{pseudo} follows a Poisson distribution convoluted with a Gaussian of mean equal to N^i_{SM} and standard deviation equal to the SM systematic uncertainty for the i-th bin. Figure 2 shows the p-value as a function of the M_{ee}.

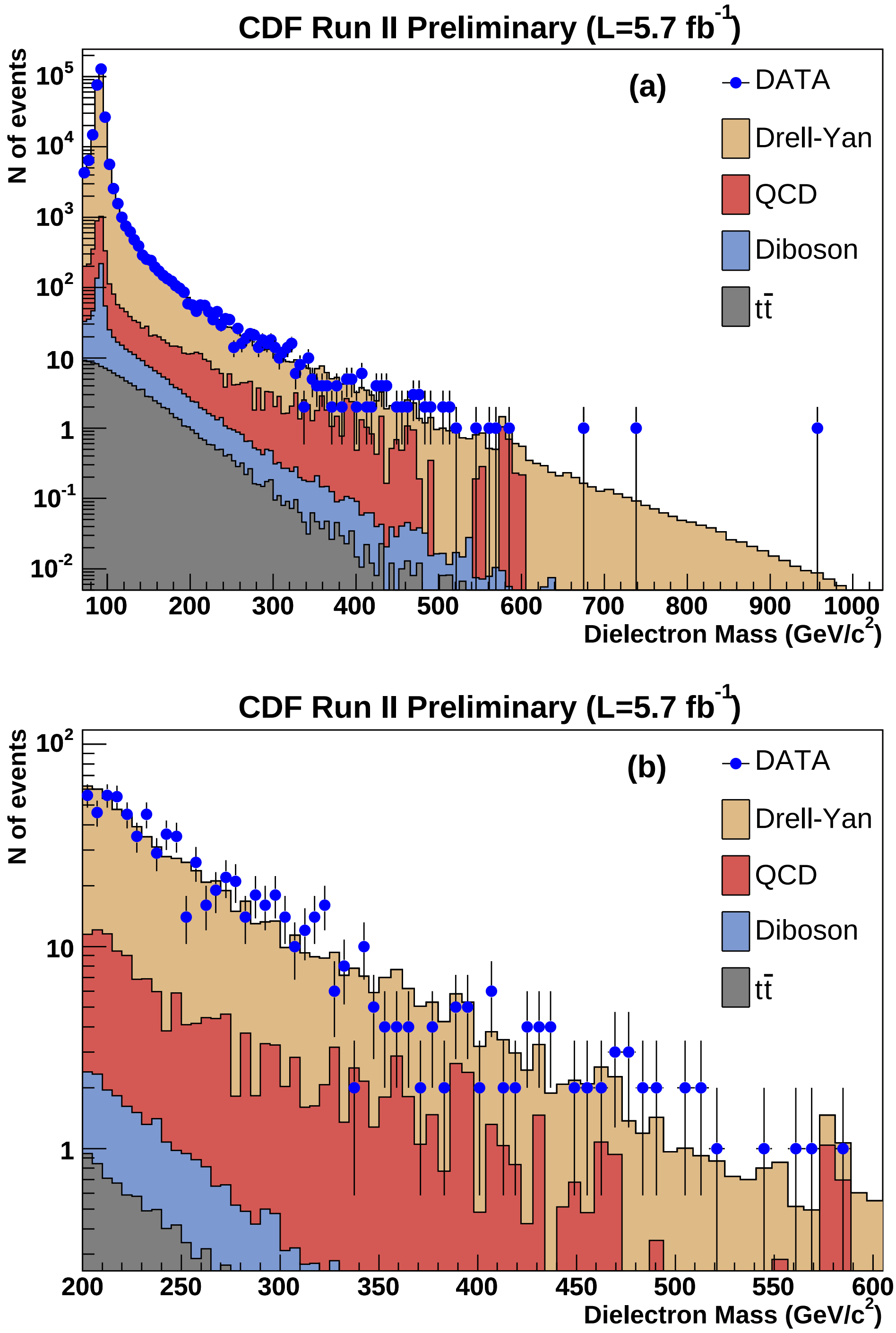


FIG. 1: (a) The dielectron mass distribution for the SM background (stacked histograms of DY, QCD, diboson, and $t\bar{t}$) and the CDF data. The QCD background is derived from CDF data. The electroweak backgrounds are estimated using MC normalized to the data luminosity times theoretical cross sections,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

The band defines 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%. Above 600 GeV/c^2, we expect 3.6 ± 0.4 events and observe three. The second most significant excess of events is observed at ∼320 GeV/c^2, as shown in Fig. 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 events. The leading-order PYTHIA cross section is multiplied by a scale ("K-factor") to correct for next-to-leading-order effects. The CDF acceptance for the dielectron RS-graviton signal, determined using MC, is ∼27%. The acceptance is approximately independent of the RS-graviton mass due to the inclusion of forward electrons, as lower-mass gravitons ($m_1 < 700$ GeV/c^2) would decay to at least one forward lepton more often than higher-mass gravitons. 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%). For gravitons masses above 200 GeV/c^2, these branching ratios are not graviton-mass-dependent. 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] results in a 50% increase in the rate of potentially produced signal. Here we present the cross section and mass limits for the dielectron channel alone and for the combined dielectron+diphoton channel.

Figure 3(a) shows the 95% confidence level (CL) cross-section ($\sigma \times \mathrm{BR}(G \to ee)$) exclusion 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 provide a solution for the fine-tuning problem. The limits are set using a frequentist method that

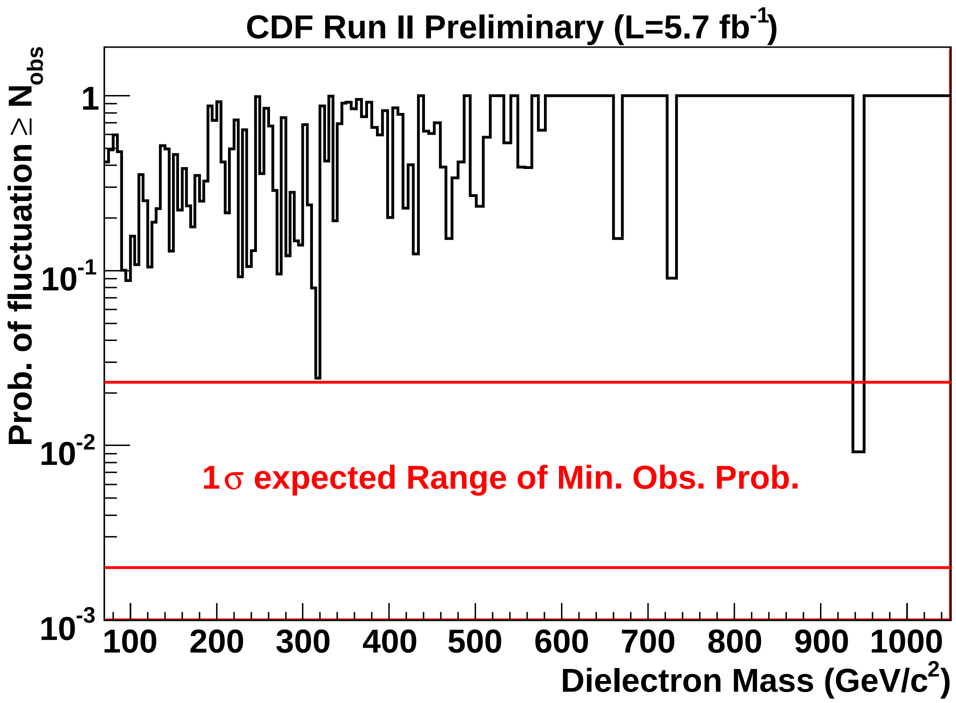
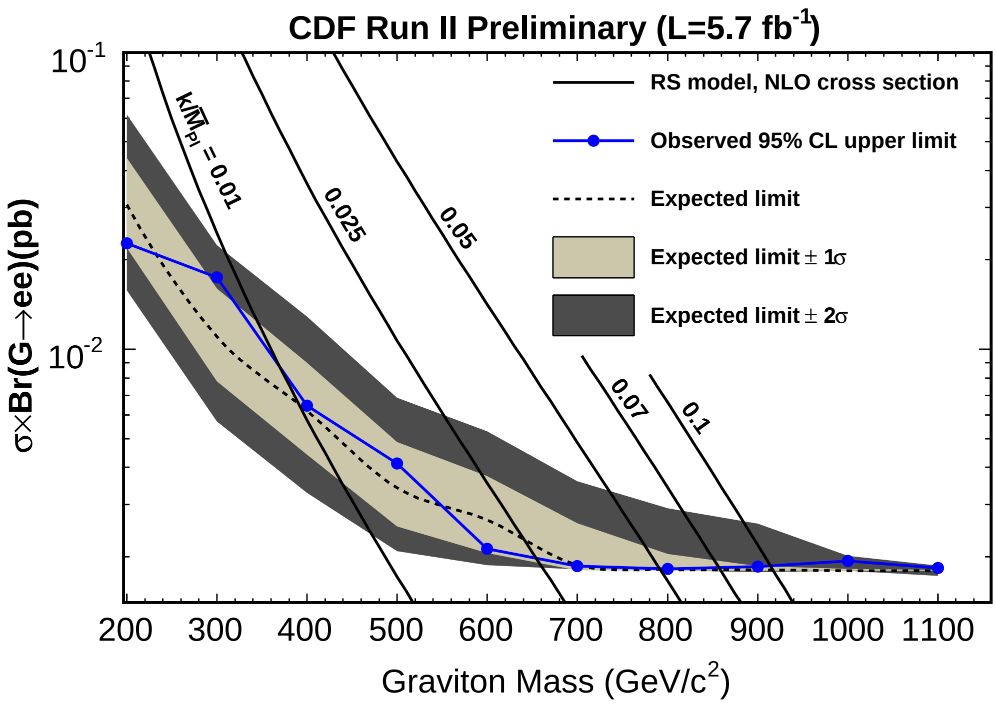


FIG. 2: The p-value as a function of the dielectron mass. The 1-σ range of expected minimum p-value seen at any bin is shown.

compares the background-only with the signal+background hypotheses, taking into account correlated background systematic uncertainties [2, 18]. 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 914 GeV/c^2, if we use proper mass-dependent RS-graviton K-factors [19, 20], and 935 GeV/c^2 assuming a fixed K-factor of 1.54 [7], for comparison with previous results [1, 7]. For $m_1 > 700$ GeV/c^2, the dielectron-only analysis excludes cross sections greater than 2 fb at the 95% CL. Above 700 GeV/c^2 the expected background and observed number of events are consistent with zero, leading to a graviton-mass-independent expected and observed limit in the investigated range of graviton masses. Figure 3(b) 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 [18]. For $k/\overline{M}_{Pl} = 0.1$, the combined m_1 limit is 1058 GeV/c^2, if we use proper mass-dependent RS-graviton K-factors, and 1092 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



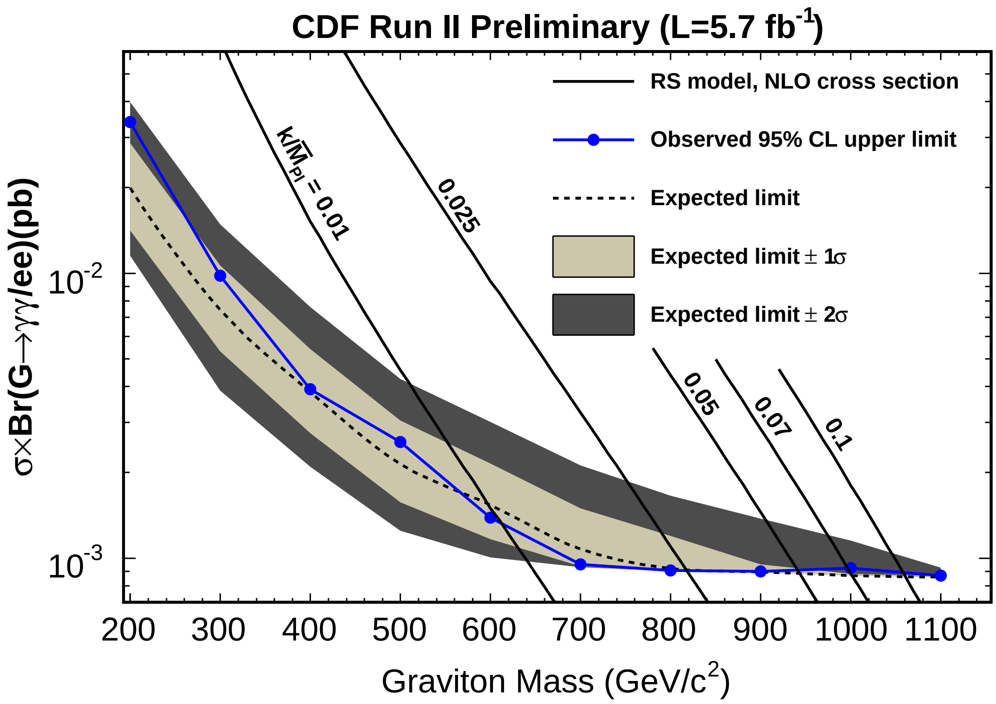


FIG. 3: (a) The upper 95% CL limit on the lightest RS-graviton production cross section from the dielectron analysis, as a function of the graviton's mass. Theoretical curves are shown for five values of the coupling $k/\overline{M}_{Pl}$ from 0.01 to 0.1. The intersections give the RS-graviton mass limits for these 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.

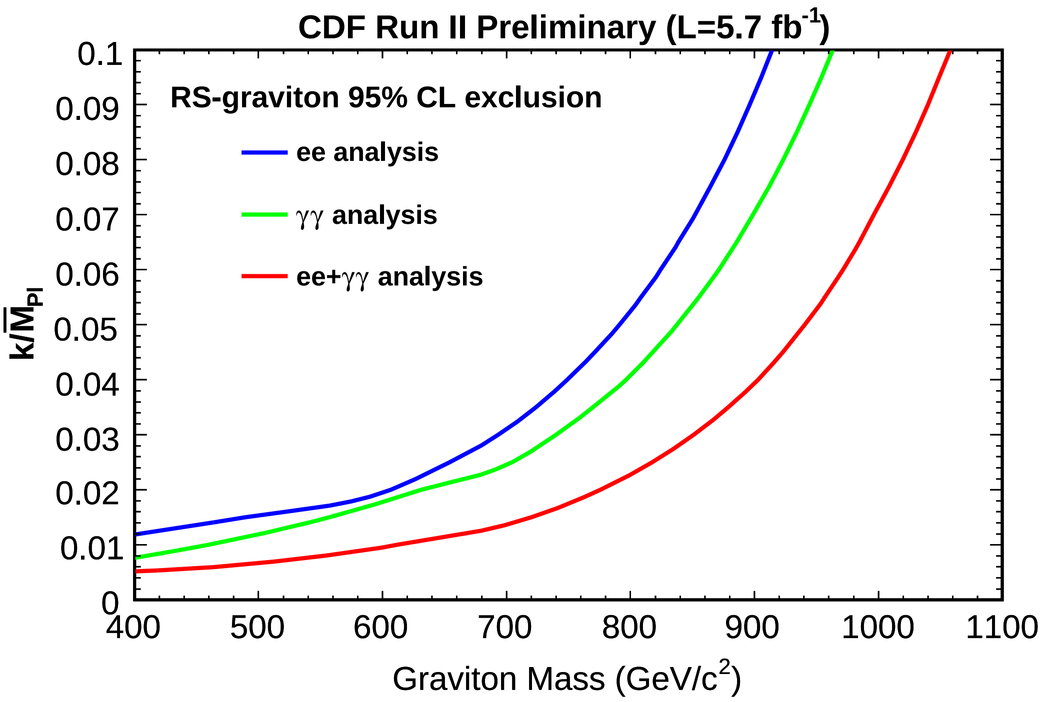


FIG. 4: The area excluded in the $k/\overline{M}_{Pl}$ vs. m_1 parameter space by the dielectron analysis, diphoton analysis, and their combination.

TABLE I: 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	612
0.025	818
0.05	941
0.07	997
0.1	1058

at the 95% CL.

Figure 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 $\sim$95 GeV/c^2 and surpasses the previous published best limit by $\sim$40 GeV/c^2. Table I 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 CDF data corresponding to an integrated luminosity of 5.7 fb^{-1}. 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 1058 or 1092 GeV/c^2, depending on the assumption on the NLO cross sections, making this result the most stringent to date.

IX. ACKNOWLEDGMENTS

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