CDF Note 10479

Search for Randall-Sundrum Gravitons in the $\mu\mu$ Channel and in the combined $\gamma\gamma + ee + \mu\mu$ channels at CDF

The CDF Collaboration
(http://www-cdf.fnal.gov)

April 7, 2011

Abstract

A search for RS-gravitons in the dimuon channel using data recorded by the CDF II detector and corresponding to an integrated luminosity of 5.7 fb^{-1} is presented. Combined with the 5.7 fb^{-1} dielectron analysis and with the 5.4 fb^{-1} diphoton analysis, the RS-graviton mass limit for the coupling $k/\overline{M}_{Pl} = 0.1$ is 1111 GeV/c^2, assuming the actual mass-dependent K-factor, or 1141 GeV/c^2 assuming a K-factor equal to 1.54, making this result in both cases the most stringent 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 note we present a search for high-mass dimuon resonances.

At hadron colliders, the search for high-mass dilepton resonances has the advantage of very low hadronic backgrounds and well-understood electroweak backgrounds. A recent CDF search [1] for Randall-Sundrum (RS) gravitons decaying to dielectrons or diphotons will benefit from the addition of the dimuon decay channel. The RS model [2] 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 dimuon resonances include the production of heavy spin-1 (e.g., Z' [3]) and spin-0 particles (e.g., Higgs boson [4] and supersymmetric particles [5]).

In this note we use the dimuon mass spectrum to exclude part of the RS-graviton parameter space. The dimuon search is combined with the recent CDF $\gamma\gamma + ee$ RS-graviton search to set the strongest limits to date. Searches for dimuon resonances with RS-graviton interpretation have been previously published by the CDF (2.3 fb^{-1}) [6] and D0 (260 pb^{-1})[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 $|\eta| = 3.6$. Drift chambers and scintillators are installed around the hadronic calorimeter to detect muons with $|\eta| < 1.4$. 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 dimuon data collected with a high-transverse momentum ($p_T \equiv p \sin\theta > 18$ GeV/c) central muon trigger and corresponding to an integrated luminosity of 5.7 fb^{-1}. To ensure a uniform trigger response, we require the central muon to have $p_T > 20$ GeV/c. The second muon 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 both the direction of the muons and their absolute value of their 3-momentum. The track of every well-reconstructed muon is required to geometrically match a stub in a muon detector, and the energy deposited in the calorimeters should be consistent with that expected from a minimum-ionizing particle. The additional transverse calorimeter energy deposited in a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ around each muon must be less than 10% of its transverse momentum. The muons 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. Each muon 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. Lower-quality muons which are not fiducial to the muon detectors are also used. Due to the limitation in determining the charge of forward or high-p_T muons, no opposite-charge requirement is imposed. Finally, a cosmic muon removal filter is applied. After the above selection, we retain 150095 dimuons in the Z-boson resonance (dimuon mass $76 < M_{\mu\mu} < 106$ GeV/c^2) and 502 dimuons with $M_{\mu\mu} > 200$ GeV/c^2.

IV. SM BACKGROUNDS

The main SM dimuon background to a high-mass dimuon signal is the Drell-Yan (DY) process $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \mu^+\mu^-$. Secondary electroweak backgrounds come from diboson production (WW, WZ, ZZ, $W\gamma^*$) with subsequent muon decays. The main hadronic background contributing to the dimuon candidate sample is the production of W+track, where the W boson decays to a muon and the track is misidentified as a muon ("fake" muon). Finally, $t\bar{t}$ events decaying to dimuons 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, muon identification scale factors and data luminosity. Good agreement between SM expectation and CDF data in the Z resonance will validate our DY prediction.

The hadronic (QCD) background is estimated using CDF data, by selecting events with an identified muon and applying to every isolated and fiducial track a probability to be misidentified as a muon. The probability for a track to fake a muon is determined from jet-rich CDF data [14].

V. SYSTEMATIC UNCERTAINTIES

The main sources of systematic uncertainty on the MC-estimated backgrounds [15] 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 ~ 10 %. The respective QCD-background systematic uncertainty is ~ 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 dimuon-mass region of interest, the results are not overly sensitive to the systematic uncertainties.

VI. DIMUON MASS SPECTRUM

Figure 1(a) shows the dimuon mass $M_{\mu\mu}$ spectrum for SM expectation and CDF data between 70 and 270 GeV/c^2. 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 $M_{\mu\mu}$ spectrum between 70 and 1000 GeV/c^2. Overall we expect 167468 ± 16747 events and we observe 158371; above 200 GeV/c^2, we expect 538 ± 89 events and observe 502.

VII. LIMITS ON RS-GRAVITON PRODUCTION

The measured $M_{\mu\mu}$ 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 1200 GeV/c^2, with a step of 100 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 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 dimuons in the dielectron+diphoton RS search [1] results in a 33% increase in the rate of potentially produced signal. Here we present the cross section and mass limits for the dimuon channel alone and for the combined dimuon+dielectron+diphoton channel.

Figure 2(a) shows the 95% confidence level (CL) cross-section ($\sigma \times \mathrm{BR}(G \rightarrow \mu\mu)$) 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 compares the background-only with the signal+background hypotheses, taking into

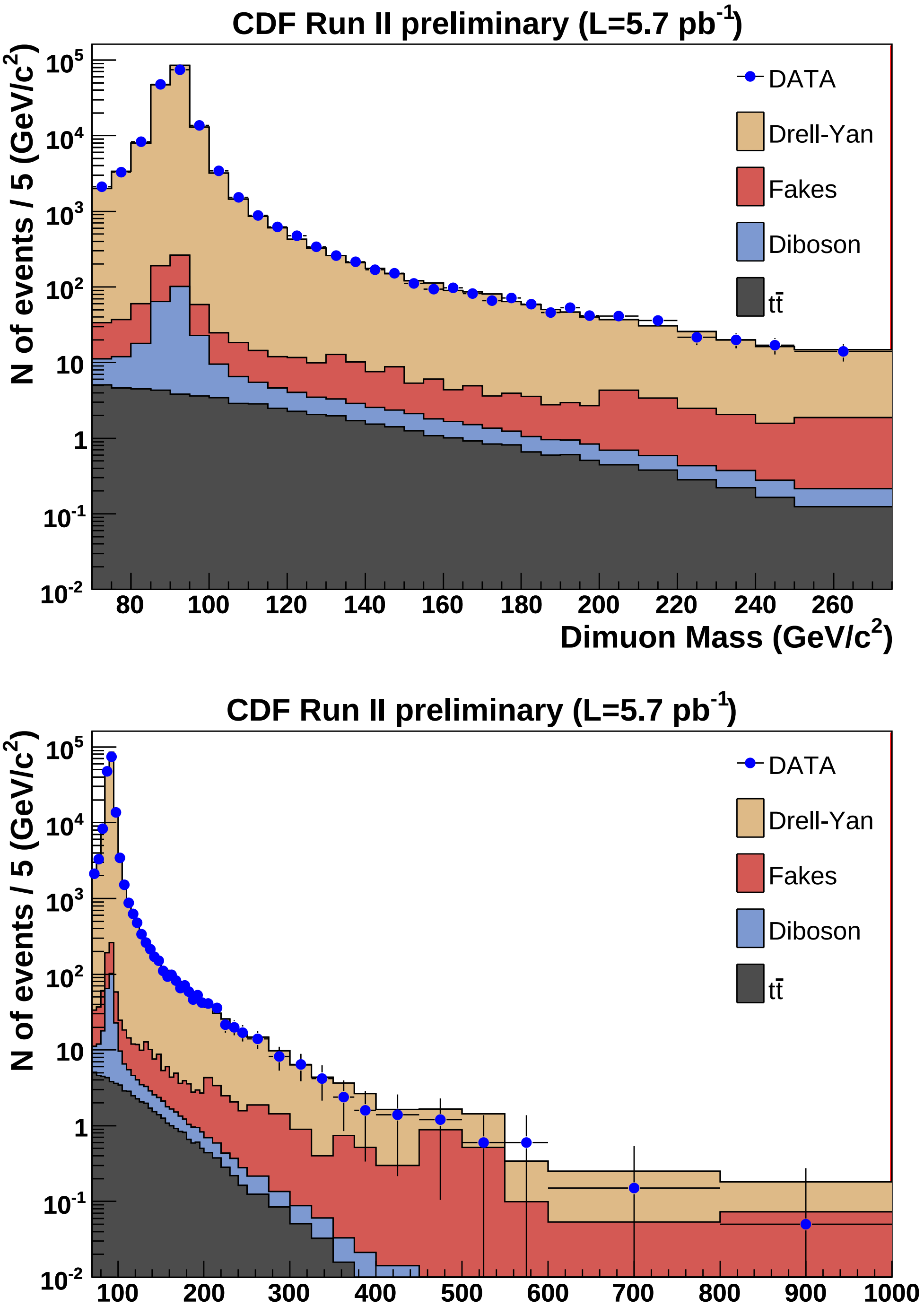

FIG. 1: (a) The dimuon mass distribution between 70 and 270 GeV/c^2 for the SM background (stacked histograms of DY, QCD, diboson, and $t\bar{t}$) and the CDF data. The QCD background is derived from CDF data. The electroweak backgrounds are estimated using MC normalized to the data luminosity times theoretical cross sections, without fitting to any part of the dimuon data distribution. (b) The dimuon mass distribution between 70 and 1000 GeV/c^2.

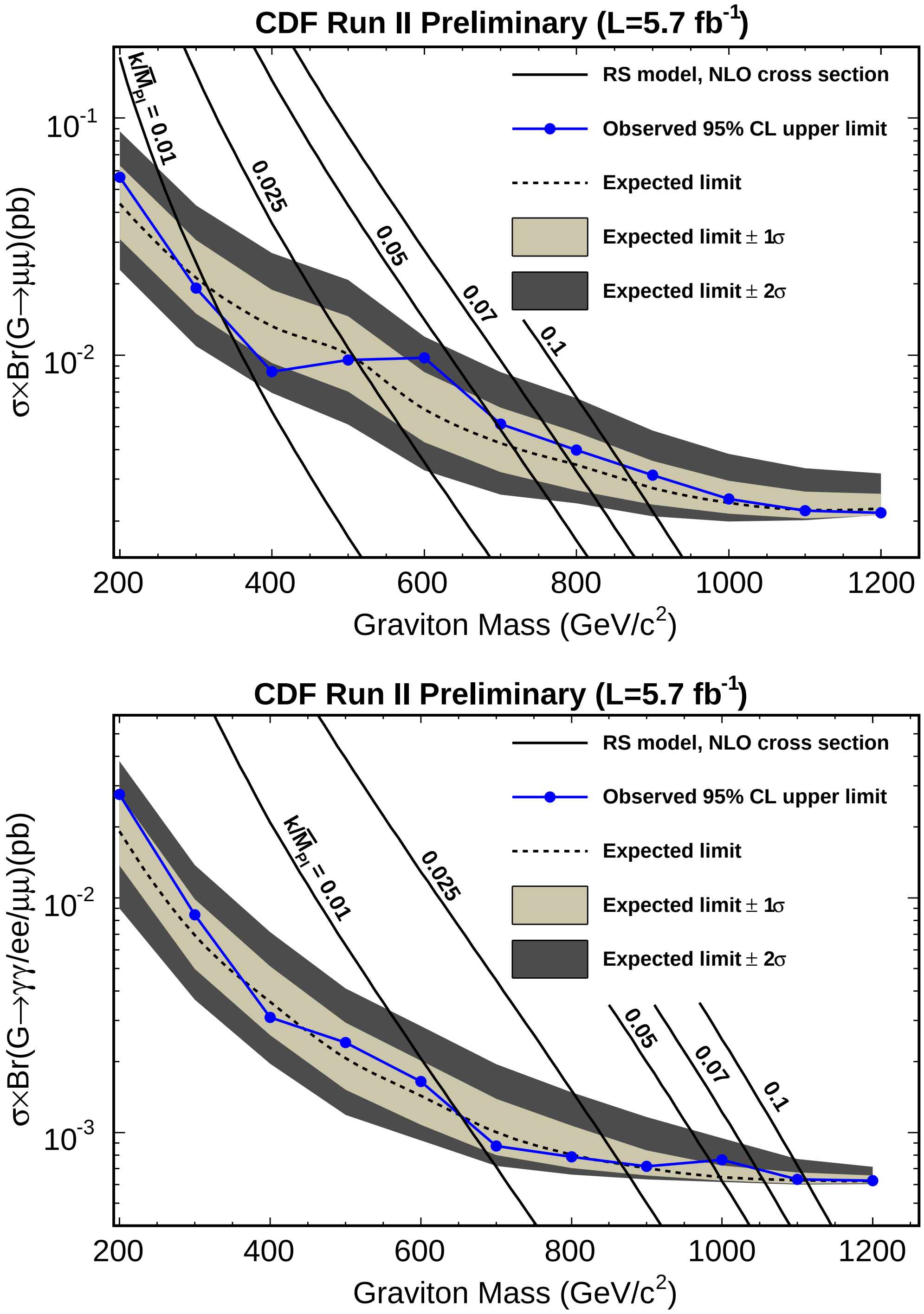

FIG. 2: (a) The upper 95% CL limit on the lightest RS-graviton production cross section from the dimuon analysis, as a function of the graviton's mass. Theoretical curves are shown for five values of the coupling $k/\overline{M}_{Pl}$ from 0.01 to 0.1. The intersections give the RS-graviton mass limits for these five hypotheses. (b) The respective cross section and mass limits for the combined $\gamma\gamma + ee + \mu\mu$ analysis. The inclusion of the dimuon analysis improves the $k/\overline{M}_{Pl} = 0.1$ limit by 56 GeV/c^2.

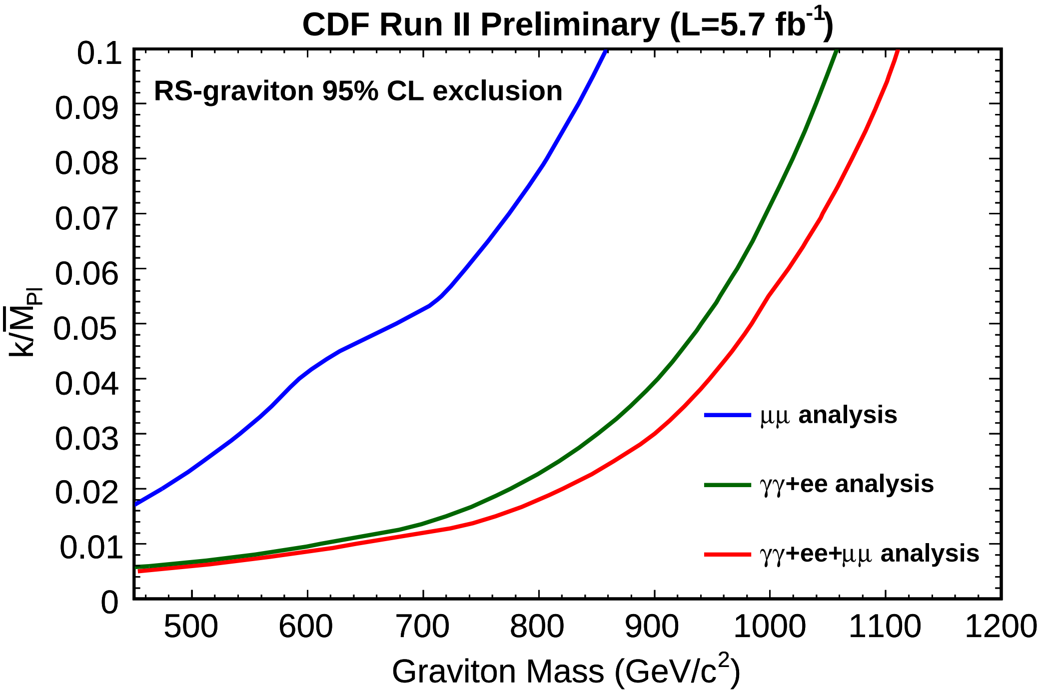

FIG. 3: The area excluded in the $k/\overline{M}_{Pl}$ vs. m_1 parameter space by the $\mu\mu$ analysis, $ee + \gamma\gamma$ analysis, and their combination.

account correlated background systematic uncertainties [16]. 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 dimuon-only m_1 limit is 859 GeV/c^2, if we use proper mass-dependent RS-graviton K-factors [17], and 886 GeV/c^2 assuming a fixed K-factor of 1.54 [7], for comparison with previous analyses [6, 7]. For $m_1 > 1150$ GeV/c^2, the dimuon-only analysis excludes cross sections greater than 2 fb at the 95% CL. Above 1150 GeV/c^2 the expected background number of events are consistent with zero, leading to a graviton-mass-independent expected limit in the investigated range of graviton masses. Figure 2(b) shows the 95% CL cross-section ($\sigma \times \text{BR}(G \rightarrow \mu\mu/ee/\gamma\gamma)$) exclusion limit from the combined $\gamma\gamma + ee + \mu\mu$ analysis. The analyses are combined as independent channels bound by a common production cross section [16]. For $k/\overline{M}_{Pl} = 0.1$, the combined m_1 limit is 1111 GeV/c^2, if we use proper mass-dependent RS-graviton K-factors, and 1141 GeV/c^2 assuming a fixed K-factor of 1.54. For $m_1 > 1150$ GeV/c^2, the combined $\gamma\gamma + ee + \mu\mu$ analysis excludes cross sections greater than 0.6 fb at the 95% CL.

Figure 3 shows the exclusions in the $k/\overline{M}_{Pl}$ vs. m_1 parameter space for the $\mu\mu$ analysis,

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

RS-graviton mass limits (GeV/c^2)		
$k/\overline{M}_{Pl}$	$\mu\mu$ analysis	$\gamma\gamma + ee + \mu\mu$ analysis
0.01	327	642
0.025	510	865
0.05	677	984
0.07	774	1046
0.1	859	1111

the $\gamma\gamma + ee$ analysis and their combination. Overall, the inclusion of muons improves the previous CDF RS-graviton limit by 56 GeV/c^2. Table I summarizes the $\mu\mu$ and the combined $\gamma\gamma + ee + \mu\mu$ RS-graviton mass limits for different values of $k/\overline{M}_{Pl}$.

VIII. CONCLUSIONS

In summary, we present a search for new resonances in the dimuon channel using CDF data corresponding to an integrated luminosity of 5.7 fb^{-1}. The dimuon mass spectrum is consistent with the SM expectation, and it is used 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 $\gamma\gamma + ee + \mu\mu$ analysis and for $k/\overline{M}_{Pl} = 0.1$ is 1111 or 1141 GeV/c^2, depending on the assumption on the NLO cross sections, making this result in both cases the most stringent to date.

IX. ACKNOWLEDGMENTS

We thank M. C. Kumar, P. Mathews, and V. Ravindran 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 Korean

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; the Academy of Finland; and the Australian Research Council (ARC).

[1] T. Aaltonen *et al.* (CDF Collaboration), submitted to Phys. Rev. Lett., arXiv:1103.4650.

[2] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999).

[3] P. Langacker, Rev. Mod. Phys. **81**, 1199 (2009).

[4] P. W. Higgs, Phys. Rev. Lett. **13**, 508 (1964).

[5] H. Baer and X. Tata, *Weak Scale Supersymmetry* Cambridge University Press, Cambridge, England (2006).

[6] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **102**, 091805 (2009).

[7] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **95**, 091801 (2005).

[8] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).

[9] R. Downing *et al.*, Nucl. Instrum. Methods A **570**, 36 (2007).

[10] T. Sjöstrand, L. Lönnblad, and S. Mrenna, PYTHIA 6.2, arXiv:hep-ph/0108264.

[11] H. Lai *et al.* (CTEQ Collaboration), Eur. Phys. J. C **12**, 375 (2000).

[12] R. Brun, R. Hagelberg, M. Hansroul, and J. Lasalle, CERN report CERN-DD-78-2-REV, (1978).

[13] A. D. Martin, W. J. Stirling, R. S. Thorne, G. Watt, Eur. Phys. J. **C63**, 189 (2009); J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999); N. Kidonakis and R. Vogt, Phys. Rev. D **78**, 074005 (2008).

[14] M. Vogel, Ph. D. thesis, University of New Mexico, expected 2011.

[15] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **79**, 052004 (2009).

[16] T. Junk, Nucl. Instrum. Methods A **434**, 435 (1999).

[17] P. Mathews, V. Ravindran, and K. Sridhar, J. High Energy Phys. 10(2005)031, M. C. Kumar, P. Mathews, V. Ravindran, Eur. Phys. J. C **49**, 599 (2007), and private communication.