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Search for Randall-Sundrum Gravitons in the Diphoton Channel at CDF

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Abstract

We report on a search for new particles in the diphoton channel using a data sample of 5.4 fb^{-1} of $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV collected using the CDF II detector at the Fermilab Tevatron. The invariant mass spectrum of the data agrees well with the standard model expectation. We set upper limits on the cross section times branching ratio for the Randall-Sundrum graviton, as a function of diphoton mass. We subsequently derive lower limits on the graviton mass of 459 GeV/c^2 and 963 GeV/c^2, at the 95% confidence level, for coupling parameters ($k/\overline{M}_{Pl}$) of 0.01 and 0.1 respectively.

The large disparity between the electroweak scale and the gravity scale (the Planck scale) is known as the hierarchy problem. In the Randall-Sundrum (RS) model [1], the hierarchy is generated by introducing one extra spatial dimension. The 5-dimensional spacetime is bounded by two 4-dimensional subspaces (or "branes", short for membranes). The standard model (SM) particles are confined to the "TeV" brane, located at $\phi = \pi$, while the Plank brane is located at $\phi = 0$, where ϕ is the angular coordinate parametrizing the extra dimension ($0 \leq |\phi| \leq \pi$). Gravity is localized on the Planck brane but can propagate in the bulk. The apparent weakness of gravity arises from the small overlap of the gravitational wave function with the TeV brane. The scale of physical phenomena on the TeV brane is generated from the Planck scale through a warp factor: $\Lambda_\pi = \overline{M}_{Pl} e^{-kr_c\pi}$, where $\Lambda_\pi \sim$ TeV, $\overline{M}_{Pl} = M_{Pl}/\sqrt{8\pi}$ is the reduced Planck scale, k is the curvature scale of the extra dimension, and r_c is the compactification radius of the extra dimension. The hierarchy is reproduced if $kr_c \simeq 12$.

The compactification of the extra dimension gives rise to a Kaluza-Klein (KK) tower of graviton states, the mass spectrum being $m_n = x_n(k/\overline{M})\Lambda_\pi$, where x_n is the n^{th} root of the first-order Bessel function, and the states couple with strength $1/\Lambda_\pi$. Two parameters determine graviton couplings and widths: the mass of the first KK graviton excitation $m_G = m_1$ and the constant $k/\overline{M}_{Pl}$. The values of k must be large enough to be consistent with the apparent weakness of gravity, but small enough to prevent the theory from becoming nonperturbative [2]. Given these considerations, we examine values in the range $0.01 \leq k/\overline{M}_{Pl} \leq 0.1$. For this range, graviton production results in a diphoton mass peak narrower than the CDF detector resolution. The spin-2 nature of the graviton, resulting in either s wave (diphoton) or p wave (dilepton) decay products, favors searches in the diphoton channel, where the branching ratio (4%) is twice that of any single dilepton channel (2%).

In the paper, we report a search for the lightest KK graviton of the RS model in the diphoton decay channel, using 5.4 fb^{-1} of integrated luminosity collected by the CDF II detector operating at $\sqrt{s} = 1.96$ TeV between February, 2002 and June, 2009. Existing lower mass limits on RS gravitons from the previous CDF analysis using 1.2 fb^{-1} of data, in the diphoton channel, are 230 GeV/c^2 and 850 GeV/c^2 for $k/\overline{M}_{Pl} = 0.01$ and 0.1 respectively at 95% confidence level (C.L.) [3]. The most recent limits from the D0 collaboration are from a combined diphoton and dielectron search using 5.4 fb^{-1} of data, with limits of 560 GeV/c^2 and 1050 GeV/c^2 for $k/\overline{M}_{Pl} = 0.01$ and 0.1 respectively [4].

The CDF II detector has a cylindrical geometry with forward-backward and azimuthal symmetry. It consists of a tracking system in a 1.4 T magnetic field, coaxial with the beam, surrounded by the calorimeters and muon detection chambers [5]. The tracking system consists of a silicon tracker (SVX-II) [6] and an open cell drift chamber (COT) [7]. The fiducial coverage of the COT is $|\eta| < 1.0$, and the silicon detector extends the tracking coverage to $|\eta| < 2.0$. The central and plug calorimeters [8] are sampling calorimeters that surround the COT; they consist of electromagnetic (EM) and hadronic sections that measure the shower energy and position in the range $|\eta| < 1.1$ and $1.2 < |\eta| < 3.6$ respectively. At the approximate electromagnetic shower maximum, the calorimeters contain fine-grained detectors [9] that measure the shower shape and centroid position in the two dimensions transverse to the shower development. Surrounding these detectors is a system of muon detectors [10]. Three levels of realtime trigger systems are used to filter events.

The collision events for this analysis were selected by at least one of four triggers. Two of the triggers require two clusters of electromagnetic energy: one requires both clusters to have transverse energy $E_T > 12$ GeV, and to be isolated in the calorimeter, while the other requires the two clusters to have $E_T > 18$ GeV, but makes no isolation requirement. To ensure very high trigger efficiency at the largest photon E_T, events are also accepted from two single photon triggers. One requires $E_T > 50$ GeV without an isolation criterion; the other requires $E_T > 70$ GeV, without an isolation criterion, and relaxed requirements on the hadronic energy associated with cluster. The combination of these triggers is effectively 100% efficient for the kinematic region used in this search for diphoton events above a mass of 100 GeV/c^2.

The triggered events are required to have been recorded while the relevant detector elements were fully operational. Both photons in each event are required to be in the central calorimeter (approximately in the region $|\eta| < 1.04$). In the selected sample, each of the two photons is required to produce a highly electromagnetic energy cluster with $E_T > 15$ GeV and together to have a reconstructed diphoton invariant mass greater than 30 GeV/c^2. Both are required to be in the fiducial region of the shower maximum detectors and to pass the following photon identification: transverse shower profiles consistent with a single photon, additional transverse energy in the calorimeter in a cone of angular radius $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ around the photon candidate < 2 GeV, and the scalar sum of the transverse momentum p_T of the tracks in the same cone < 2 GeV/c. Photons are required to produce isolated energy clusters in the shower maximum detector.

The selected data consist of 47920 events. The diphoton invariant mass distribution for these events, histogrammed in bins equivalent to the mass resolution (approximated by $0.13\sqrt{m} \oplus 0.02m$ GeV, where m is diphoton mass in GeV/c^2) is shown in Fig.1.

The expected number of RS graviton events, as a function of graviton mass, are estimated using the `PYTHIA 6.226` event generator [11], with `CTEQ5L` parton distribution functions (PDFs) [12], and processed by the `GEANT 3` based CDF II detector simulation. The combined acceptance and selection efficiency for RS diphoton events increases from $0.12 \pm 0.01_{\text{sys}}$ for gravitons of mass 200 GeV/c^2 to $0.33 \pm 0.03_{\text{sys}}$ for gravitons of mass 1100 GeV/c^2. The simulated photon selection efficiency is corrected by comparing the measured and Monte Carlo simulated detector response to electrons from Z boson decays, since a pure sample of reconstructed photons is not available, and the characteristics of energy deposited in the calorimeter by electrons are almost identical to those of photons. The $Z^0 \to e^+e^-$ sample is also used to calibrate the electromagnetic energy scale. The diphoton energy scale in data and Monte Carlo is corrected by tuning the $Z^0 \to e^+e^-$ mass peak to the world average. The largest systematic uncertainties on the expected number of graviton events arise from the luminosity measurement (6%) and the uncertainty associated with the initial and final

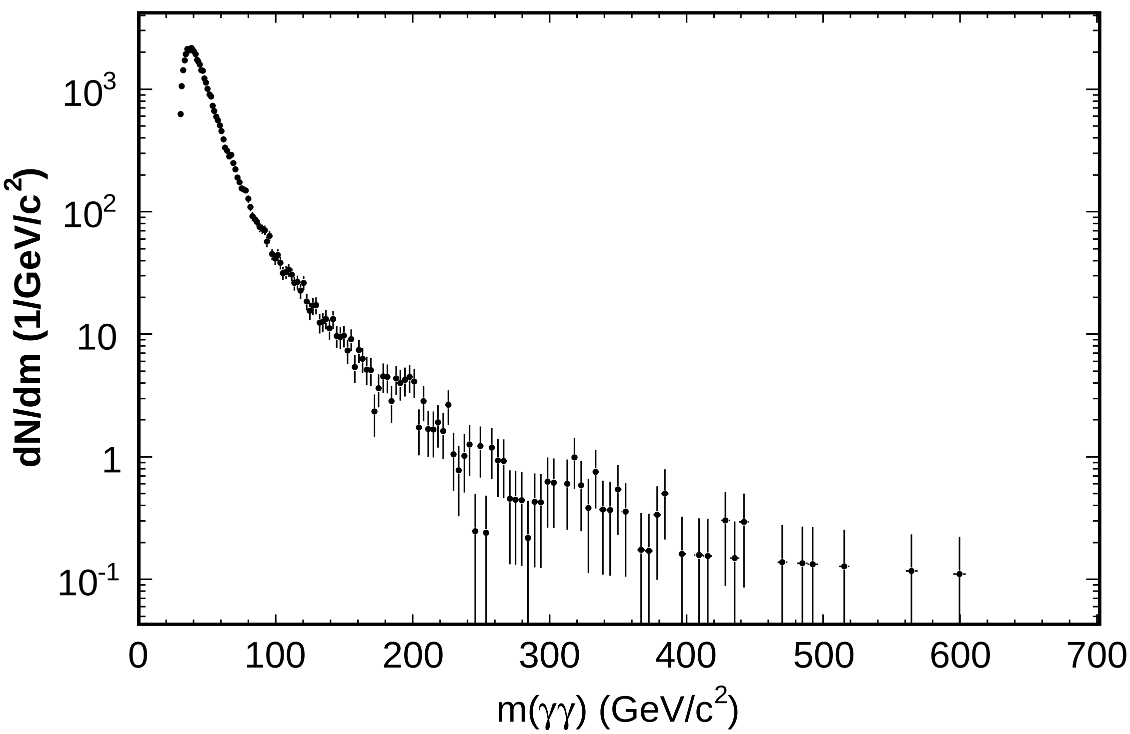

Figure 1: The diphoton invariant mass distribution of events, histogrammed in bins of approximately one unit of calorimeter mass resolution.

state radiation (ISR/FSR). The latter uncertainty is determined from the variation in the efficiency when varying the parton shower parameters in PYTHIA and decreases from 8% for gravitons of mass 200 GeV/c^2 to 4% for gravitons of mass 1100 GeV/c^2.

There are two significant background components in the diphoton data sample. The first is SM diphoton production. We estimate the shape of this background with the DIPHOX next-to-leading-order (NLO) Monte Carlo [13] calculation. This program calculates the cross section of diphoton production in the hadronic collisions as a function of mass. To extrapolate to the highest masses, the mass distribution of DIPHOX calculation is fitted to a product of a polynomial and the sum of five exponentials. The fitted mass spectrum is then corrected by an efficiency function derived from a SM diphoton sample generated by PYTHIA and processed through the full detector simulation. The second background component arises from the misidentification of one or two jets as photons. The shape of this background is parameterized with a product of a polynomial and the sum of two exponentials. This function form is justified using a sample of photonlike jets obtained by loosening the photon selection criteria, then removing the events which pass all the signal selection requirements.

To find the most accurate description of the background for setting limits, we fit the invariant mass spectrum of the data to a sum of the DIPHOX shape and the photonlike jets shape. The normalization of each component and the shape of the photonlike jets are allowed to vary in the fit. We fit the mass spectrum in the range $m_{\gamma\gamma} > 100$ GeV/c^2 since the RS gravitons have been excluded at the 95% C.L. in the lower mass region by previous searches.

Figure 2 shows the observed mass spectrum with the fitted total background overlaid. The best fit SM background normalization is consistent with the DIPHOX calculation. Also shown in the figure is the systematic uncertainty on the total background, which is approximately 20%. The systematic uncertainty arises predominantly from the choice of the Q^2 scales used in the DIPHOX calculation for low mass diphoton events and from the choice of the parton distribution functions (PDFs) for high mass diphoton events.

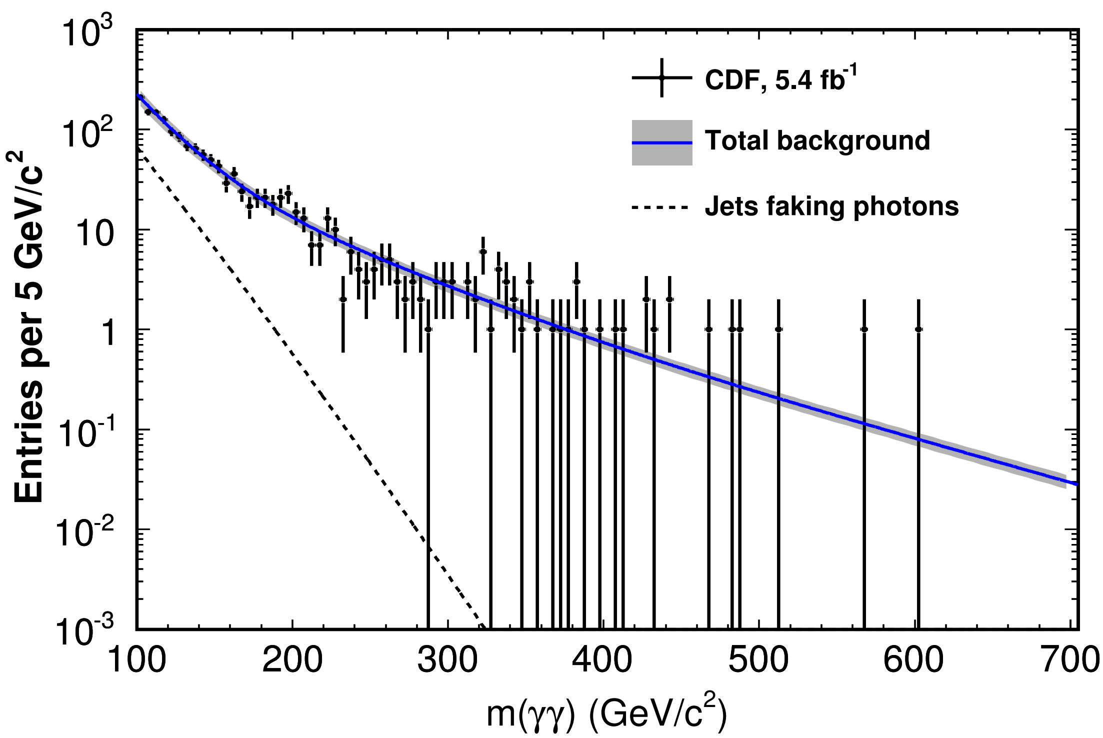

Figure 2: The diphoton invariant mass spectrum with the fitted total background overlaid. The points are the data. The dotted line shows the jets which fake photons, and the solid line shows this background plus the DIPHOX SM diphoton distribution. The gray band shows the uncertainty on the total background.

In the region around 200 GeV/c^2 there is an excess of events in the invariant mass spectrum. The probability that this excess is exclusively due to background fluctuation is 0.013. This probability is within the expected range for the minimal probability that

$k/\overline{M}_{Pl}$	Lower Mass Limit (GeV/c^2)
0.1	963
0.07	899
0.05	838
0.025	704
0.01	459

Table 1: The 95% C.L. lower limits on the mass of the RS graviton for the specified values of $k/\overline{M}_{Pl}$.

the background alone could give rise to the observed number of events in the diphoton mass region 150-650 GeV/c^2 based on studies performed with pseudo-experiments using only the background prediction.

We use the CL_s limit-setting technique [14] to set the upper limits for the production cross section of RS gravitons times the branching fraction into the $\gamma\gamma$ final state using the diphoton mass spectrum. In this method, the data are compared against two models at a time. One is the null hypothesis H_0, which asserts that the SM describes the data, while the other is the signal plus background hypothesis H_1. The probability ratio

$$CL_s = \frac{P_{H_1}(\Delta\chi^2 \geq \Delta\chi^2_{obs})}{P_{H_0}(\Delta\chi^2 \geq \Delta\chi^2_{obs})}. \tag{1}$$

is used to set the limits. The probabilities are calculated by generating pseudo-experiments taking into account systematic uncertainties on signal and background predictions. $\Delta\chi^2$ is calculated by comparing the data (either in the real experiment or in the pseudo-experiment) against H_0 or H_1. The 95% C.L. upper limit corresponds to the cross section which gives $CL_S = 0.05$.

The result is shown in Fig.3, as a function of graviton mass, along with the theoretical cross section times branching ratio for RS gravitons with $k/\overline{M}_{Pl}$ set to 0.1, 0.07, 0.05, 0.025 and 0.01. The leading-order graviton production cross section is multiplied by a K-factor [15], decreasing from 1.54 at 200 GeV/c^2 to 0.98 at 1000 GeV/c^2, to correct for diagrams at higher-order in α_s. From the limit on $\sigma \times Br(G \rightarrow \gamma\gamma)$, lower mass bounds are derived for the first excited state of the RS graviton as a function of the parameter $k/\overline{M}_{Pl}$. The 95% C.L. excluded region in the $k/\overline{M}_{Pl}$ and graviton mass plane is displayed in Fig. 4, with the mass limits summarized in Table 1.

In conclusion, we have searched for evidence of an anomalous peak in the diphoton mass spectrum using approximately 5.4 fb^{-1} of data collected by the CDF II detector at the Fermilab Tevatron. We find no evidence of new physics. We evaluate one model of hypothetical new diphoton production and exclude RS gravitons below masses ranging from 459 to 963 GeV/c^2, for a coupling parameter $k/\overline{M}_{Pl}$ of 0.01 to 0.1, at the 95% C.L.. This results in a significant improvement, at high mass, over the previous best available limit.

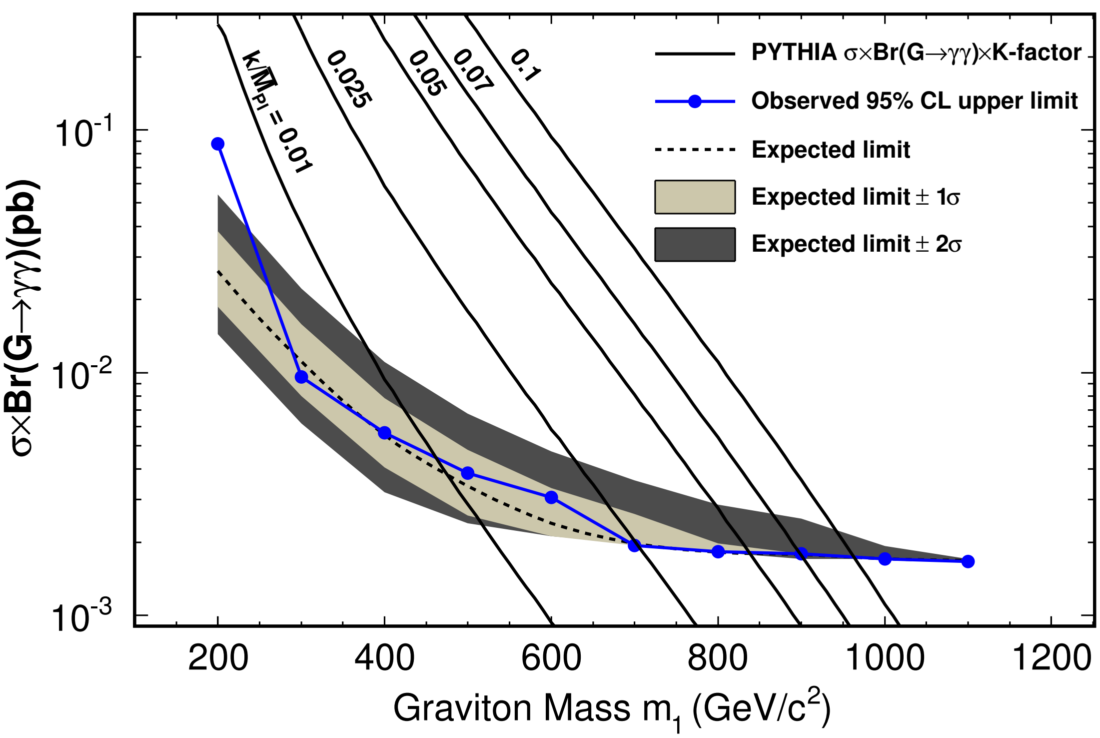

Figure 3: The 95% C.L. upper limit on the production cross section times branching fraction of an RS model graviton decaying to diphotons ($\sigma \times Br(G \rightarrow \gamma\gamma)$) as a function of graviton mass. Also shown are the predicted ($\sigma \times Br$) curves for $k/M_{Pl} = 0.01$, 0.07, 0.05 and 0.1.

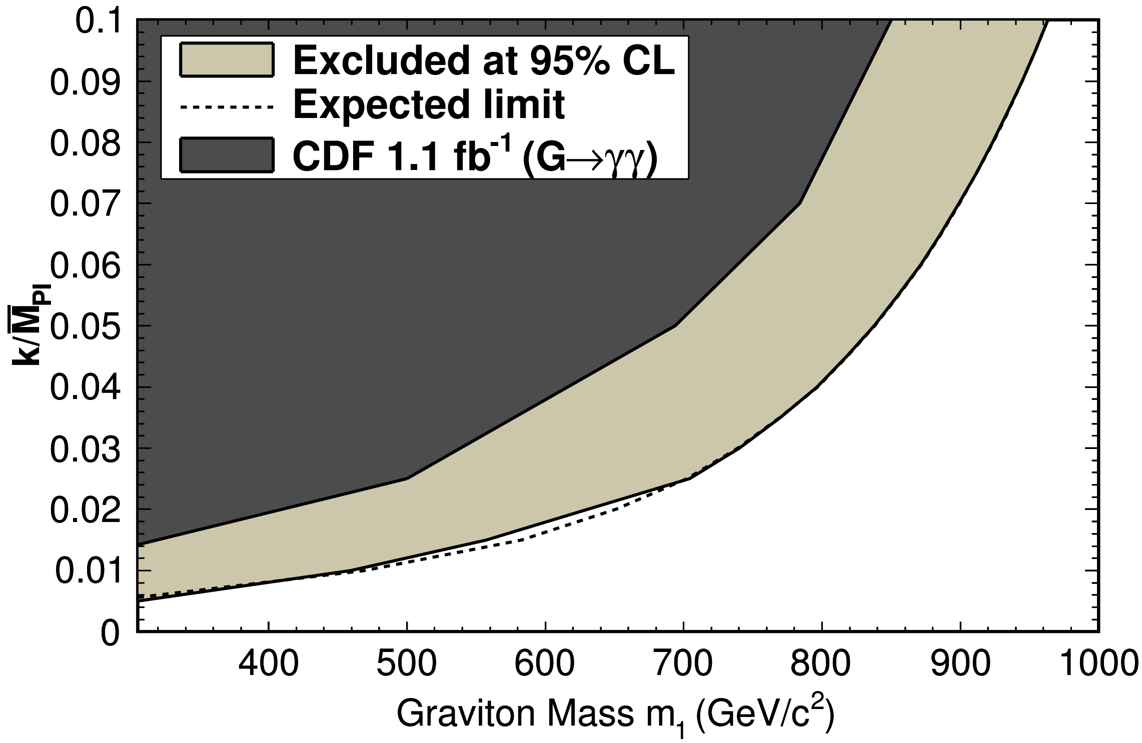

Figure 4: The 95% C.L. excluded region in the plane of k/M_{Pl} and graviton mass.

References

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

[2] H. Davoudiasl, J. L. Hewett and T. G. Rizzo, Phys. Rev. Lett. **84**, 2080 (2000).

[3] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **99**, 171801 (2007).

[4] V. M. Abazov *et al.* [The D0 Collaboration], arXiv:1004.1826 [hep-ex].

[5] A cylindrical coordinate system, (r, ϕ, z) is used with origin at the geometric center of the detector. r is the radius from the nominal beam line, ϕ is the azimuthal angle, and $+z$ points along the direction of the proton beam. The polar angle θ with respect to the proton beam defines the pseudorapidity η which is given by $\eta = -\ln[\tan(\theta/2)]$.

[6] A. Sill, Nucl. Instrum. Meth. A **447**, 1 (2000).

[7] T. Affolder *et al.*, Nucl. Instrum. Meth. A **526**, 249 (2004).

[8] L. Balka *et al.* [CDF Collaboration], Nucl. Instrum. Meth. A **267**, 272 (1988); S. Bertolucci *et al.* [CDF Collaboration], Nucl. Instrum. Meth. A **267**, 301 (1988); M. G. Albrow *et al.* [CDF Collaboration], Nucl. Instrum. Meth. A **480**, 524 (2002).

[9] G. Apollinari *et al.*, Nucl. Instrum. Meth. A **412**, 515 (1998).

[10] G. Ascoli *et al.*, Nucl. Instrum. Meth. A **268**, 41 (1988).

[11] T. Sjostrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).

[12] J. Pumplin *et al.*, JHEP **0207**, 012 (2002).

[13] T. Binoth *et al.*, Eur. Phys. J. C **16**, 311 (2000).

[14] T. Junk, Nucl. Instrum. Meth. A **434**, 435 (1999); A. L. Read, J. Phys. G **28**, 2693 (2002).

[15] M. C. Kumar *et al.*, Nucl. Phys. B **818**, 28 (2009); M. C. Kumar *et al.*, Phys. Lett. B **672**, 45 (2009); private communication with the authors.