Searching for the elusive graviton

Edgar Carrera for the DØ Collaboration
Florida State University, Tallahassee, FL 32306, USA

We present a search for large extra dimensions in the single photon plus missing transverse energy channel (Kaluza-Klein graviton production) performed using 2.7 fb$^{-1}$ of data collected by the DØ experiment at the Fermilab Tevatron collider. At 95% C.L., we set limits on the fundamental Planck scale $M_D$ from 970 GeV to 816 GeV for two to eight extra dimensions.

1. INTRODUCTION

The large unexplained difference between the effective Planck scale in the 4-dimensional space-time ($M_{Pl} \sim 10^{16}$ TeV) and the electroweak scale ($\sim 1$ TeV), generally known as the hierarchy problem of the Standard Model (SM), served as the main motivation for the emergence of theories of large extra dimensions (LED), also known as ADD theories [1]. They postulate the presence of $n$ extra spatial dimensions with sizes ($R$) comparable to the electroweak scale. While SM particles are bound to the ordinary 3-dimensional space (3-d brane), gravitons can penetrate the additional volume in detriment of the strength of the gravitational field in the 3-d brane. The hierarchy problem is solved, since the fundamental Planck scale in the $(4+n)$-dimensional space-time ($M_D$), which could be of the order of the electroweak scale, is concealed by the large size of the extra volume: $M_D^2 = 8 \pi M_{Pl}^n R^n$.

The compactification of the extra space forces the gravitational field to populate only certain energy modes known as Kaluza-Klein (KK) modes. Towers of these modes behave like massive, noninteracting, stable particles, the KK gravitons ($G_{KK}$), whose production can be inferred in a collider detector by the presence of missing transverse energy ($E_T$).

This review constitutes an update for a previous analysis [2], where we searched for large extra dimensions in the exclusive (monophoton) channel $q\bar{q} \rightarrow \gamma G_{KK}$ in 1 fb$^{-1}$ of data, collected with the DØ detector at the Fermilab Tevatron collider. The present study uses the same analysis techniques on 1.7 fb$^{-1}$ of additional data. At the end, we present the final results as a combination of both analyses (2.7 fb$^{-1}$ of data). Recently, the CDF collaboration analyzed 2 fb$^{-1}$ of data to set 95% C.L. lower limits on $M_D$, from 1080 GeV to 900 GeV for two to six extra dimensions [4]. Searches for LED in other final states have been performed by collaborations at the Tevatron [5, 6] and the CERN LEP collider [7].

2. EVENT SELECTION

A photon is identified in the detector as a calorimeter cluster with at least 90% of its energy in the electromagnetic (EM) part. The calorimeter isolation variable, $I = [(E_{01}^{\text{tot}} - E_{02}^{\text{em}}) - \alpha \cdot l]/E_{01}^{\text{em}}$, is required to be less than 0.07. In this equation, $E_{01}^{\text{tot}}$ denotes the total energy deposited in the calorimeter in a cone of radius $R = \sqrt{\Delta \eta^2 + (\Delta \phi)^2} = 0.4$, $E_{02}^{\text{em}}$ is the EM energy in a cone of radius $R = 0.2$, $l$ is the instantaneous luminosity, and $\alpha$ is a constant that takes different values for the central ($|\eta| < 1.1$) and end-cap regions ($1.3 < |\eta| < 4$) of the calorimeter. The track isolation variable, defined as the scalar sum of the transverse momenta of all tracks that originate from the interaction vertex in an annulus of 0.05 < $R$ < 0.4 around the cluster, is less than 2 GeV. Only EM clusters in the central region of the detector with both transverse and longitudinal shower shapes consistent with those of a photon are considered. The cluster has neither an associated track in the central tracking system, nor a significant density of hits in the SMT and CFT systems consistent with the presence of a track. Additionally, it is required that the EM cluster matches an energy deposit in the central preshower (CPS) system.

The photon sample is created by selecting events with only one photon with $p_T > 90$ GeV, and at least one reconstructed interaction vertex consistent with direction of the photon given by the CPS system. No jets with
$p_T > 15$ GeV are allowed in the event. Jets are reconstructed using the iterative midpoint cone algorithm with a cone size of 0.5. The missing transverse energy, which is computed from calorimeter cells with $\eta < 4$ and corrected for EM and jet energy scales, is required to be at least 70 GeV. The applied $E_T$ requirement guarantees negligible multijet background in the final candidate sample, while being almost fully efficient for signal selection. Events containing muons, cosmic ray muons, or tracks with $p_T > 8$ GeV are rejected.

3. ANALYSIS

The EM pointing algorithm uses the fine transverse and longitudinal segmentation of the calorimeter and the CPS system to measure the direction of the EM shower. It calculates the distance of closest approach (DCA) to the $z$ axis (along the beam line) and predicts the $z$ position of the interaction vertex in the event independently of the tracker information. After standardized selection requirements, large backgrounds to the $\gamma + E_T$ signal, which originate from cosmic ray muons and beam halo particles (non-collision) depositing energy in the calorimeter, are still present. The discriminating power of the EM pointing variables help reduce this background significantly and very efficiently. The remaining non-collision events, as well as the contribution from $W/Z + \text{jet}$ events where the jet is misidentified as a photon, are estimated by performing a linear template fit to the data where we exploit the differences in the shapes of the DCA distributions (Fig. 1). The procedure is described in detail in [2].

![DCA distribution for the selected events in 1.7 fb$^{-1}$ of data (points with statistical uncertainties). The different histograms represent the estimated background composition from the template fit to this distribution. The inset figure compares the individual template shapes.](image)

The backgrounds arising from the process $Z + \gamma \rightarrow \nu\bar{\nu} + \gamma$, which gives the same signature as the signal, or from $W + \gamma$ where the lepton from the $W$ boson decay is not detected, are estimated from a sample of Monte Carlo (MC) events generated with PYTHIA [8], and corrected for luminosity profile differences with data. Additionally, we apply scale factors to account for the differences between the efficiency determination in data and simulation. $W \rightarrow e\nu$ background, where the electron is misidentified as a photon, is estimated from data using a sample of isolated electrons and the measured rate of electron-photon mis-identification.

We generate signal events for two to eight extra dimensions using a modified version of PYTHIA [8]. Table I gives the final numbers for data and backgrounds. The main sources of systematic uncertainty are the uncertainty in the photon identification efficiency (5%), the uncertainty in the total integrated luminosity (6.1%), and the uncertainty in the signal acceptance from the PDFs (4%). For the standard model background estimated from MC an uncertainty of 7% in the cross section is also included.

The total efficiency for the MC signal is 0.38 ± 0.04. In order to combine this efficiency with the one in the analysis described in [2], we perform a luminosity-weighted average of the two values and add an extra systematic uncertainty of 5% due to correlations. The combined efficiency is then 0.43 ± 0.05. Fig. 2 shows the photon $p_T$ distribution for $\gamma + E_T$ events.
Table I: Data and estimated backgrounds

| Background                  | Number of expected events (1.7 fb$^{-1}$) | Number of expected events (combined analysis, 2.7 fb$^{-1}$) |
|-----------------------------|-------------------------------------------|-------------------------------------------------------------|
| $Z + \gamma \rightarrow \nu \nu + \gamma$ | $17.4 \pm 2.2$                            | $29.5 \pm 2.5$                                             |
| $W \rightarrow e\nu$       | $4.7 \pm 1.7$                             | $8.5 \pm 1.7$                                              |
| Non-collision               | $3.8 \pm 1.8$                             | $6.6 \pm 2.3$                                              |
| Misidentified jets          | $0.91 \pm 0.23$                           | $3.1 \pm 1.5$                                              |
| $W + \gamma$               | $0.72 \pm 0.15$                           | $2.22 \pm 0.3$                                             |
| Total Background            | $27.5 \pm 3.3$                            | $49.9 \pm 4.1$                                             |
| Data                        | $22$                                      | $51$                                                       |

Figure 2: Photon $p_T$ distribution for the final candidate events with 2.7 fb$^{-1}$ of data after all the selection requirements. Data points show statistical uncertainties. The LED signal is stacked on top of SM backgrounds.

The combined analysis, with the SM backgrounds stacked on top of each other. We employ the modified frequentist approach [8] to set limits at the 95% C.L. on the production cross section for the signal, assuming the leading-order theoretical cross section. Table II and Fig. 3 summarize the limit setting results.

To conclude, we have conducted an update to the analysis described in [2] on a search for LED in the $\gamma + E_T$ channel, finding no evidence for their presence. The updated limits show significant improvement from our previous

Figure 3: The expected and observed lower limits on $M_D$ for LED in the $\gamma + E_T$ final state. CDF limits with 2 fb$^{-1}$ of data (monophoton channel) [4], and the LEP combined limits [7] are also shown.
study and are competitive for \( n > 4 \).

Table II: Summary of limit calculations.

| \( n \) | 1 fb\(^{-1} \) [2] observed (expected) cross section limit (fb) | 1 fb\(^{-1} \) [2] observed (expected) cross section limit (GeV) | 2.7 fb\(^{-1} \) observed (expected) cross section limit (fb) | 2.7 fb\(^{-1} \) observed (expected) cross section limit (GeV) | CDF 2 fb\(^{-1} \) [4] observed limit (GeV) |
|---|---|---|---|---|---|
| 2 | 27.6 (23.4) | 884 (921) | 19.0 (14.6) | 970 (1037) | 1080 |
| 3 | 24.5 (22.7) | 864 (877) | 20.1 (14.7) | 899 (957) | 1000 |
| 4 | 25.0 (22.8) | 836 (848) | 20.1 (14.9) | 867 (916) | 970 |
| 5 | 25.0 (24.8) | 820 (821) | 19.9 (15.0) | 848 (883) | 930 |
| 6 | 25.4 (22.3) | 797 (810) | 18.2 (15.2) | 831 (850) | 900 |
| 7 | 24.0 (23.1) | 797 (801) | 15.9 (14.9) | 834 (841) | — |
| 8 | 24.2 (21.9) | 778 (786) | 17.3 (15.0) | 804 (816) | — |

Acknowledgments

The author wishes to thank Alexey Ferapontov, Yuri Gershtein and Yurii Maravin for their guidance and help, and the staffs at Fermilab and collaborating institutions.

References

[1] N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B 429, 263 (1998).
[2] V.M Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 101, 011601 (2008).
[3] V.M. Abazov et al. (D0 Collaboration), Nucl. Instrum. Methods Phys. Res. A 565, 463 (2006).
[4] T. Aaltonen et al. (CDF Collaboration), arXiv:0807.3132v1[hep-ex] (2008).
[5] B. Abbott et al. (D0 Collaboration), Phys. Rev. Lett. 86, 1156 (2001); ibid 90, 251802 (2003); ibid 95, 161602 (2005).
[6] D. Acosta et al. (CDF Collaboration), Phys. Rev. Lett. 97, 171802 (2006).
[7] LEP Exotica Working Group, URL: http://lepexotica.web.cern.ch/LEPEXOTICA/notes/2004-03/ed_note_final.ps.gz and references therein.
[8] T. Sjöstrand et al., Comput. Phys. Commun. 135, 238 (2001); Stephen Mrenna, private communication.
[9] W. Fisher, FERMILAB-TM-2386-E (2007); T. Junk.