Experimental limits on the fundamental Planck scale in large extra dimensions

Douglas M. Gingrich

Centre for Particle Physics, Department of Physics, University of Alberta,
Edmonton, AB T6G 2E1 Canada
TRIUMF, Vancouver, BC V6T 2A3 Canada
ingrich@ualberta.ca

May 3, 2014

Abstract I present an up to date set of limits on the fundamental Planck scale $M_D$. The best limit for each number of extra dimensions $n$ is shown in bold font. For $n = 2$, $M_D > 4.2$ TeV; $n = 3$, $M_D > 3.3$ TeV; $n = 4$, $M_D > 2.9$ TeV; $n = 5$, $M_D > 2.8$ TeV; $n = 6$, $M_D > 2.5$ TeV; and for $7 \leq n \leq 8$, $M_D \gtrsim 0.8$ TeV.

Keywords: black holes, extra dimensions, beyond Standard Model

1 Introduction

For black hole studies, we are interested in the $D$-dimensional fundamental Planck scale $M_D$. This scale is related to the derived Planck scale $M_{Pl}$ in models of large extra dimensions by

$$M_{Pl}^2 = 8\pi R^n M_D^{2+n}, \quad (1)$$

where $n = D - 4$ is the number of extra dimensions of the same size $R$. The four-dimensional effective Planck scale is given by Newton’s constant $G_N = M_{Pl}^{-2}$.

Using $M_{Pl} = 1.22090 \times 10^{16}$ TeV and $\hbar c = 1.97326968 \times 10^{-4}$ TeV-fm gives

$$M_D = \left[5.93089 \left(\frac{197.326968 \, \mu m}{R}\right)^n \right]^{\frac{1}{n+2}} \times 10^{\frac{15(2-n)}{n+2}} \, \text{TeV} \quad (2)$$

and

$$R = \left[\frac{5.93089 \, \text{TeV}^{n+2}}{M_D^{n+2}}\right]^{\frac{1}{n}} \times 197.326968 \times 10^{\frac{15(2-n)}{n}} \, \mu m. \quad (3)$$

Limits on $M_D$ or $R$ have been set by direct gravity measurements, experiments at accelerators, and constraints from astrophysics and cosmology. The astrophysical and cosmological limits are high, particularly for two or three extra dimensions. However, they are based on a number of assumptions so the results are only order of magnitude estimates. Thus, I will not consider further astrophysical or cosmological limit.
2 Direct gravity measurements

The most straightforward observable effect of the large extra dimensions is the modification of Newton’s gravitational attraction law at very short distance. Gravity measurements are sensitive to the largest extra dimension. The Eöt-Washington group constrain the size of the largest extra dimension to $R \leq 44 \mu\text{m}$ at the 95% confidence level \[1\]. This completely rules out TeV-scale gravity with one large extra dimension. For two large extra dimensions, they obtain $M_* \geq 3.2$ TeV. The PDG transforms this into the limit $R < 30 \mu\text{m}$, which corresponds to $M_D > 4.0$ TeV in the case of $n = 2$. The sensitivity to three extra dimensions of equal size is only $M_D > 4 \times 10^{-3}$ TeV.

3 Limits from accelerator experiments

The HERA experiments have set limits on the Kaluza-Klein ultraviolet-cutoff scale but not on $M_D$. I thus consider only the results from the LEP, Tevatron, and LHC collider experiments.

In $e^+e^-$ processes with real graviton emission, the cross section is directly sensitive to the number of extra dimensions and the fundamental scale of gravity. Virtual graviton exchange is sensitive to the ratio $\lambda/M_H$. $M_H$ is an ultraviolet-cutoff scale, which is not equivalent to $M_D$ – but should be of the same order of magnitude – and $\lambda$ is a coupling constant, which depends on the underlying theory of gravity. In pp collisions, direct graviton emission also depends on $M_D$, while virtual graviton exchange does not depend on $M_D$. The dependence on the ultraviolet-cutoff is more complicated but the ideas are similar.

3.1 Combined LEP results

I consider only the direct graviton emission searches from LEP2 \[2, 3, 4\]. The results from ALEPH, DELPHI, and L3 have been combined \[5\] and are shown in the Table 1.

3.2 Tevatron results

I consider only the direct graviton emission searches from Run II of the Tevatron (Table 1). The latest CDF search is in jets plus missing transverse energy final states \[6\]. They use a $K$-factor (ratio of cross sections as calculated at the next-to-leading order and leading order) of 1.3. The latest DØ search is in mono-photon and missing transverse energy final states \[7\]. The $K$-factor is include in the uncertainties.

3.3 LHC results

I consider only the direct graviton emission searches from the LHC experiments (Table 1). Using approximately 5 fb$^{-1}$ of data at 7 TeV pp centre-of-mass energy, ATLAS \[8\] and

\[1\]Ref. \[5\] is found at http://lepexotica.web.cern.ch/LEPEXOTICA/notes/2004-03/ed\_note\_final.ps.gz
CMS [9] have search results in mono-photon and missing transverse momentum final states. Both experiments include similar $n$-dependent $K$-factors in the results. ATLAS [10] and CMS [11] also have search results in mono-jet and missing transverse momentum final states for the same beam energy and luminosity. Since the experiments use different $K$-factors, I give the limits using leading order cross sections in Table 1.

### 3.4 Black hole searches

ATLAS and CMS have searched for direct black hole production. The limits on $M_D$ from the searches are largely model dependent. In the case of classical black hole models, the limits on $M_D$ depend on the threshold production mass $M_{th}$, as well as $n$. CMS has also set such limits for quantum black hole production models using di-jet events [12]. In models of quantum black hole production, ATLAS has taken the threshold mass as $M_D$, and searched in di-jet events [13]. Since the models are speculative, I do not consider them as giving limits on $M_D$.

Table 1: Upper limits on $M_D$ at the 95% confidence limit.

| $n$ | $M_D$ [TeV] | Mono-photon | Mono-jet |
|-----|-------------|-------------|----------|
|     |             | LEP | CDF | DØ  | ATLAS | CMS | ATLAS | CMS |
| 2   | 1.60        | 1.40 | 0.884 | 1.93 | 4.17    | 4.08 |
| 3   | 1.20        | 1.15 | 0.864 | 1.83 | 1.73    | 3.32 | 3.24 |
| 4   | 0.94        | 1.04 | 0.836 | 1.86 | 1.67    | 2.89 | 2.81 |
| 5   | 0.77        | 0.98 | 0.820 | 1.89 | 1.84    | 2.66 | 2.52 |
| 6   | 0.66        | 0.94 | 0.797 | 1.89 | 1.64    | 2.51 | 2.38 |
| 7   |             |     |     | 0.797 |        |      |      |
| 8   |             |     |     | 0.778 |        |      |      |

### Acknowledgments

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada.

### References

[1] D. Kapner, T. Cook, E. Adelberger, J. Gundlach, B. R. Heckel, et al., *Tests of the gravitational inverse-square law below the dark-energy length scale*, Phys. Rev. Lett. 98 (2007) 021101 [arXiv:hep-ph/0611184 [hep-ph]]
[2] ALEPH Collaboration, A. Heister et al., *Single- and Multi-Photon Production in e⁺ e⁻ Collisions at √s up to 209 GeV*, Eur. Phys. J. C **28** (2003) 1.
[3] DELPHI Collaboration, J. Abdallah et al., *Photon events with missing energy in e⁺ e⁻-collisions at √s = 130-GeV to 209-GeV*, Eur. Phys. J. C **38** (2005) 395–411, arXiv:hep-ex/0406019 [hep-ex].
[4] The L3 Collaboration, P. Achard et al., *Single photon and multiphoton events with missing energy in e⁺e⁻-collisions at LEP*, Phys. Lett. B **587** (2004) 16–32, arXiv:hep-ex/0402002 [hep-ex].
[5] LEP Exotica Working Group, ALEPH, DELPHI, L3, and OPAL Collaborations, *Combination of LEP Results on Direct Searches for Large Extra Dimensions*, 2004. CERN Note LEP Exotica WG 2004-03.
[6] CDF Collaboration, T. Aaltonen et al., *Search for large extra dimensions in final states containing one photon or jet and large missing transverse energy produced in pp collisions at √s = 1.96-TeV*, Phys. Rev. Lett. **101** (2008) 181602, arXiv:0807.3132 [hep-ex].
[7] The DØ Collaboration, V. Abazov et al., *Search for large extra dimensions via single photon plus missing energy final states at √s = 1.96-TeV*, Phys. Rev. Lett. **101** (2008) 011601, arXiv:0803.2137 [hep-ex].
[8] The ATLAS Collaboration, G. Aad et al., *Search for dark matter candidates and large extra dimensions in events with a photon and missing transverse momentum in pp collision data at √s = 7 TeV with the ATLAS detector*, arXiv:1209.4625 [hep-ex].
[9] The CMS Collaboration, S. Chatrchyan et al., *Search for Dark Matter and Large Extra Dimensions in pp Collisions Yielding a Photon and Missing Transverse Energy*, Phys. Rev. Lett. **108** (2012) 261803, arXiv:1204.0821 [hep-ex].
[10] The ATLAS Collaboration, G. Aad et al., *Search for dark matter candidates and large extra dimensions in events with a jet and missing transverse momentum with the ATLAS detector*, arXiv:1210.4491 [hep-ex].
[11] The CMS Collaboration, S. Chatrchyan et al., *Search for dark matter and large extra dimensions in monojet events in pp collisions at √s = 7 TeV*, JHEP **1209** (2012) 094, arXiv:1206.5663 [hep-ex].
[12] The CMS Collaboration, *Search for narrow resonances and quantum black holes in inclusive and b-tagged dijet mass spectra from pp collisions at √s = 7 TeV*, arXiv:1210.2387 [hep-ex].
[13] The ATLAS Collaboration, G. Aad et al., *ATLAS search for new phenomena in dijet mass and angular distributions using pp collisions at √s = 7 TeV*, arXiv:1210.1718 [hep-ex].