Experimental bounds on large extra dimensions from di-jet event production in hadron collisions

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Abstract. We discuss the new dominant bounds that can be derived on the coefficient of the effective operator generated by tree-level graviton exchange in large extra dimensions from \(pp \rightarrow jj\) data at LHC: \(M_T > 2.1\) TeV (ATLAS after 3.1/pb of integrated luminosity), \(M_T > 3.3\) TeV (ATLAS after 36/pb of integrated luminosity), \(M_T > 3.4\) TeV (CMS after 36/pb). We clarify the role of on-shell graviton exchange and compare the full graviton amplitude to data, setting bounds on the fundamental quantum-gravity scale.

1. Introduction
With the start of the LHC program, experiments are already testing directly some of the theoretical ideas about new physics at the electroweak scale. In one popular scenario Standard Model fields are confined on a 3-dimensional brane, while gravity propagates in the full \(D\)-dimensional space, with \(\delta\) flat and compactified extra spatial dimensions \((D = 4 + \delta)\) [1]. This scenario allows for quantum gravity at the weak scale and could therefore be a solution to the Higgs mass hierarchy problem. Even without knowledge of the exact model for quantum gravity at the weak scale, we can make some definite predictions for collider experiments which can provide valid descriptions in certain kinematical domains. We can identify five different kinds of LHC signals which allow for a theoretical interpretation in terms of \(D\)-dimensional gravity (for details we refer to [2]).

(i) Missing \(p_T\) from emission of massive gravitons constituting the Kaluza-Klein tower.
(ii) Tree-level exchange of gravitons generating the effective dimension-8 operator \(T\) [3, 4, 5]
\[
\mathcal{L}_{\text{int}} = c_T \times T = \frac{8}{M_T} \times \frac{1}{2} \left( T_{\mu\nu} T^{\mu\nu} - \frac{T_{\mu} T_{\nu}}{\delta + 2} \right),
\]
where \(T_{\mu\nu}\) is the SM energy-momentum tensor. In most cases the parameter \(M_T\) cannot be computed without knowledge of the underlying quantum-gravity theory.

(iii) Virtual graviton exchanges at one-loop level induce dimension-6 effective operators, as opposed to the dimension-8 \(T\) operator [6]. For pure graviton virtual intermediate states, a unique dimension-6 operator is generated
\[
\mathcal{L} = c_T \times \Upsilon, \quad \Upsilon = \frac{1}{2} \left( \sum_f \bar{f} \gamma_5 f \right) \left( \sum_f \bar{f}^\mu \gamma_5 f \right),
\]
\(\delta\) Speaker.

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where $f$ is any SM quark or lepton. As in the case of tree-level graviton exchange, the coefficient $c_\Upsilon$ can be related to the fundamental parameters $M_D$ and $\delta$ only by specifying a cutoff procedure.

(iv) **Dijet events at large invariant mass and large rapidity separation.** In this kinematic regime, gravitational scattering can be reliably computed in the eikonal approximation [7].

(v) **Black holes.** Black-hole formation and decay is expected to occur in the transplanckian region when the impact parameter becomes smaller than the corresponding Schwarzschild radius [8].

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**Table 1. Tree-level graviton exchange**: 95% CL limits on the coefficient $M_T$ (known as Hewett normalization [5]) of the dimension-8 operator $T$ of eq. (1) for positive and negative interference. The last three limits are derived in [2].

| Experiment          | Process                        | $e^+$ | $e^-$ |
|---------------------|--------------------------------|-------|-------|
| LEP [9]             | $e^+e^- \rightarrow \gamma\gamma$ | 0.93 TeV | 1.01 TeV |
| LEP [10]            | $e^+e^- \rightarrow e^+e^-$       | 1.18 TeV | 1.17 TeV |
| H1 [11]             | $e^+p$ and $e^-p$                | 0.74 TeV | 0.71 TeV |
| ZEUS [12]           | $e^+p$ and $e^-p$                | 0.72 TeV | 0.73 TeV |
| CDF [13]            | $p\bar{p} \rightarrow e^+e^-,\gamma\gamma$ | 0.99 TeV | 0.96 TeV |
| DØ [13]             | $p\bar{p} \rightarrow e^+e^-,\gamma\gamma$ | 1.28 TeV | 1.14 TeV |
| DØ [14]             | $p\bar{p} \rightarrow jj$        | 1.48 TeV | 1.48 TeV |
| CMS at 7 TeV with 40/pb [15] | $pp \rightarrow \mu^-\mu^+$    | 1.6 TeV | 1.6 TeV |
| CMS at 7 TeV with 36/pb [16] | $pp \rightarrow \gamma\gamma$ | 1.74 TeV | 1.71 TeV |
| LEP combined [17]   | $e^+e^- \rightarrow e^+e^-$       | 11.3  | 11.5  |
| LEP combined [17]   | $e^+e^- \rightarrow \mu^+\mu^-$ | 16.4  | 12.7  |
| LEP combined [17]   | $e^+e^- \rightarrow \ell^+\ell^-$ | 17.2  | 15.1  |
| LEP combined [17]   | $e^+e^- \rightarrow b\bar{b}$   | 15.3  | 11.5  |
| H1 [11]             | $e^+p$ and $e^-p$                | 2.5   | 3.9   |
| ZEUS [12]           | $e^+p$ and $e^-p$                | 4.6   | 5.3   |
| DØ [18]             | $p\bar{p} \rightarrow e^+e^-$    | 4.7   | 5.5   |
| CDF [18]            | $p\bar{p} \rightarrow \ell^+\ell^-$ | 4.5  | 5.6  |
| CCFR [19]           | $\nu N$ scattering               | 3.7   | 5.9   |
| DØ [18]             | $p\bar{p} \rightarrow jj$       | 3.2   | 3.1   |
| ATLAS at 7 TeV with 3.1/pb | $pp \rightarrow jj$          | 5.3   | 4.2   |
| CMS at 7 TeV with 36/pb | $pp \rightarrow jj$         | 11    | 8.1   |
| **combined**        |                                | 22.4  | 15.7  |

**Table 2. Loop-level graviton exchange**: 95% CL limits on the coefficient $|c_\Upsilon/4\pi|^{-1/2}$ (in TeV) of the dimension-6 operator $\Upsilon$ of eq. (2) for positive and negative values of $c_\Upsilon$.

In its first stage with low statistics, LHC is particularly sensitive to the operator in eq. (1), because its high dimensionality means that the high energy of the LHC collisions is the key factor.
Figure 1. Left (right): $pp \rightarrow jj$ angular distribution at ATLAS with $M_{jj} > 1.2$ TeV (at CMS with $M_{jj} > 2.2$ TeV) binned as a function of the angular distance $\chi$. The experimental data (crosses) are compared to the SM prediction (black histogram) and to the expectation including virtual graviton effects at tree level.

2. Fit to the graviton-exchange effective operator

We compare the first LHC data to the new physics described by eq.s (1) and (2). The tree-level exchange of virtual gravitons described by the Lagrangian of eq. (1) mediates the processes: $pp \rightarrow \ell^+\ell^-, pp \rightarrow \gamma\gamma, pp \rightarrow jj$. The main point is that the $pp \rightarrow \ell^+\ell^-$ and $pp \rightarrow \gamma\gamma$ cross sections are significantly lower than the $pp \rightarrow jj$ cross section. Indeed requiring final states with invariant mass greater than 1 TeV, jets, leptons and photons with $\eta < 2.5$, and additionally requiring $|\eta_1 - \eta_2| < 1.2$ for the jets, we find:

$$\sigma = \left( \frac{2 \text{TeV}}{M_T} \right)^8 \times \begin{cases} \quad 12.5 \text{ fb} & \text{for } pp \rightarrow jj \\ \quad 10.4 \text{ fb} & \text{for } pp \rightarrow \mu^+\mu^- \\ \quad 21.3 \text{ fb} & \text{for } pp \rightarrow \gamma\gamma \end{cases} . \quad (3)$$

This large difference in cross sections is due partly to trivial flavor and color factors, and partly to the fact that the processes are mediated by the operator of dimension 8 in eq. (1). In particular $pp \rightarrow jj$ benefits from the high energy of the initial partons $uu$ in the $t$-channel process.

ATLAS [20] and CMS [21, 22] have searched for the effect of contact interactions in the angular distribution of dijet events, in the variable $\chi \equiv \exp|y_1 - y_2|$ where $y_1,2$ are the two jet rapidities. Due to the dominance of Coulomb-like scattering in the SM, these distributions are expected to be almost flat in the case of QCD, while contact interactions give a deviation from the flat distribution. Data for the $\chi$ distribution from ATLAS are reported in fig. 1a together with the SM expectation at next-to-leading order [20]. We compare data with the theoretical expectation and we compute the 95% CL bound on the coefficient of the $T$ operator. We find the bound $M_T > 2.1$ TeV reported in table 1, which significantly exceeds all previous bounds. CMS $pp \rightarrow jj$ data after 36 pb$^{-1}$ have been presented in [22] and are here plotted in fig. 1b. We can reliably estimate the resulting bound, $M_T > 3.4$ TeV,
3. Fit to the full graviton-exchange amplitude

In view of its experimental significance, in [2] the theory behind eq. (1) is reconsidered. In full generality, tree-level graviton-exchange leads to a scattering amplitude of the form

\[ A = S(s) \left( T_{\mu\nu} T^{\mu\nu} - \frac{T_{\mu}^\mu T_{\nu}^\nu}{\delta + 2} \right), \]

where the function \( S \) is obtained by summing over all the Kaluza-Klein (KK) tower of gravitons. If the typical energy resolution of the experiment is broader than the mass separation between two KK states, then the sum can be approximated with an integral over the extra-dimensional momentum \( q \) of the graviton. In the opposite case of well separated narrow resonances, it is more precise to square the amplitude before integrating. This guess is confirmed by comparison with the exact result for the sum in the cases in which it can be explicitly performed. This gives an enhancement which however corresponds to on-shell graviton emission, and thus must be retained only when those decay promptly in the detector. On the other hand it actually corresponds to missing energy and not dijet signal if the emitted gravitons decay far away. All this is clarified in [2], to which we refer for more details.

The integral in \( S \) is UV divergent for \( \delta > 1 \) extra dimensions, so we regularize them by including only KK excitations with mass \( m = |q| \) below an arbitrary cut-off \( \Lambda \), which parametrizes the onset of the unknown quantum-gravity physics. A small (large) ratio \( \Lambda/M_D \) effectively means that quantum gravity is weakly (strongly) coupled [6]. In view of the high dimensionality of the operator, the dominant LHC bound comes from the highest energy events, and it is appropriate to retain the full amplitude, including the dependence on the cut-off \( \Lambda \). Formulæ for the cross sections from tree-level graviton effects in any number of extra dimensions can be found in the appendix of ref. [24]. We implement them in Pythia8 [25] and compare the data with the full graviton-exchange amplitude. The results of our fit are shown in fig. 2.

4. Conclusion

We found that the very first LHC data about \( pp \rightarrow jj \) improve significantly previous bounds on the coefficient of the effective dimension-8 operator \( T \) generated by virtual graviton exchange, and predicted by theories with extra dimensions.

We also went beyond the effective-operator approximation and computed the full amplitude generated by tree level graviton exchange in terms of a cut-off parameter \( \Lambda \), which is the maximal KK graviton mass. We clarified that the enhanced effect of lighter gravitons that can be produced on-shell must be included only when such gravitons decay within the detector. Fig. 2 shows the resulting LHC bounds in the \((M_D, \Lambda/M_D)\) plane.

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Figure 2. The shaded area is the bound from virtual graviton exchange at CMS (continuous line denoted as ‘C’, data after 36/\text{pb}), ATLAS (long-dashed line denoted as ‘A’, data after 36/\text{pb}). Vertical blue line: bound from graviton emission (as summarized in table 1 of [6]). Red line: Naive Dimensional Analysis estimate of LEP bound from loop graviton exchange. Upper shading: NDA estimate of the non-perturbative region.

References

[1] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 429 (1998) 263 [hep-ph/9803315].
[2] R. Franceschini, G. F. Giudice, P. P. Giardino, P. Lodone and A. Strumia [hep-ph/11014919].
[3] G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B 544, 3 (1999) [hep-ph/9811291].
[4] T. Han, J.D. Lykken and R. Zhang, Phys. Rev. D59 (1999) 105006 [arXiv:hep-ph/9811350].
[5] J.L. Hewett, Phys. Rev. Lett. 82 (1999) 4765 [arXiv:hep-ph/9811356].
[6] G. F. Giudice and A. Strumia, Nucl. Phys. B 663 (2003) 377 [hep-ph/0301232].
[7] G. F. Giudice, R. Rattazzi, J. D. Wells, Nucl. Phys. B630 (2002) 293-325 [hep-ph/0112161].
[8] S. B. Giddings, S. D. Thomas, Phys. Rev. D65, 056010 (2002) [hep-ph/0106219]. S. Dimopoulos, G. L. Landsberg, Phys. Rev. Lett. 87, 161602 (2001). [hep-ph/0106295]. See also T. Banks, W. Fischler, hep-th/9906038.
[9] The LEP-II Diphoton Working Group, LEP2FF/02-02.
[10] ALEPH 2001-019 CONF 2001-016; DELPHI 2001-094 CONF 522; L3 Note 2759; OPAL Physics Note PN471.
[11] H1 Collaboration, ICHEP02, abstract 979.
[12] ZEUS Collaboration, EPS 2001, abstract 602.
[13] G. Landsberg, for the D0 and CDF collaborations, arXiv:hep-ex/0412028.
[14] D0 collaboration, Phys. Rev. Lett. 103 (2009) 191803 [arXiv:0906.4819].
[15] CMS collaboration, http://cdsweb.cern.ch/record/1335097/files/EXO-10-020-pas.pdf.
[16] CMS collaboration, arXiv:1103.4279. See also: CMS-PAS-EXO-09-004, “Search for Large Extra Dimensions in the Diphoton Final State”.
[17] LEP Working Group LEP2FF/02-03.
[18] J.A. Green, for the CDF and D0 Collaborations, arXiv:hep-ex/0004035.
[19] K.S. McFarland et al. [NuTeV Collaboration], arXiv:hep-ex/9806013.
[20] ATLAS collaboration, Phys. Lett. B694 (2011) 327 [arXiv:1009.5069].
[21] CMS collaboration, Phys. Rev. Lett. 105 (2010) 262001 [arXiv:1010.0203].
[22] CMS collaboration, arXiv:1102.2020. See also the talk by G. Landsberg, “Quest for New Physics with the First LHC data at CMS”, 24/1/2011.
[23] ATLAS collaboration, arXiv:1103.3864.
[24] G. F. Giudice, T. Plehn, A. Strumia, Nucl. Phys. B706 (2005) 455 [arXiv:hep-ph/0408320].
[25] PYTHIA: T. Sjostrand, S. Mrenna, P. Skands, Comput. Phys. Com. 178, 852 (2008) [arXiv:0710.3820].