Physical Science International Journal
11(3): 1-10, 2016, Article no.PSIJ.28096
ISSN: 2348-0130

SCIENCEDOMAIN *international*
www.sciencedomain.org

Models of Extra Dimensions and Searches for Kaluza-Klein Modes at the LHC

Obikhod Tetiana[1*] and Petrenko Ievgenii[1]

[1]*Institute for Nuclear Research NAS of Ukraine, 03680 Kiev, Ukraine.*

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/PSIJ/2016/28096
Editor(s):
(1) Roberto Oscar Aquilano, School of Exact Science, National University of Rosario (UNR), Department of Science and Technology, Argentina.
(2) Stefano Moretti, School of Physics and Astronomy, University of Southampton, UK.
Reviewers:
(1) Paul Murad, Morningstar Applied Physics Inc., LLC, Vienna, Austria.
(2) Manuel Malaver de la Fuente, Maritime University of the Caribbean, Venezuela.
Complete Peer review History: http://www.sciencedomain.org/review-history/15740

Original Research Article

Received 1st July 2016
Accepted 3rd August 2016
Published 10th August 2016

ABSTRACT

We have considered the theories of extra dimensions from Large Extra Dimensions and Randall-Sundrum models to the E8 × E8 heterotic sting theory identified with the 11-dimensional M-theory. Within the three models of extra dimensions and with the help of computer program PYTHIA were calculated the production cross sections for Kaluza-Klein gravitons and Kaluza-Klein vector bosons with the cms energy range 2 -14 TeV at the LHC. It was performed a comparison of the theoretical predictions with the data of computer modeling and found a satisfactory agreement. Searches on heavy gauge bosons performed by the ATLAS and CMS experiments collected during 2012 at the LHC were used for comparison with our calculations for masses of Kaluza-Klein gauge boson. The obtained results are important for future searches of Kaluza-Klein gravitons and vector bosons with the cms 14 TeV at the LHC.

Keywords: *Models of extra dimensions; heterotic string theory; M-theory; Kaluza Klein graviton; Kaluza Klein vector boson; computer modeling.*

**Corresponding author: E-mail: obikhod@kinr.kiev.uam, tanyamaliuta@gmail.com;*

1. INTRODUCTION

For unification of gravity and electromagnetism by Kaluza-Klein (KK) theory [1] was proposed the unification of geometric symmetries with internal symmetries for treatment all observables as symmetry motions in extended space with extra dimensions. This idea was used for inclusion non-abelian gauge fields and then generalized by superstring theory for resolution the hierarchy problem of theoretical high energy physics. The most studied superstring compactification is heterotic string theory compactified on a Calabi-Yau space in six-dimensions. The other attractive theory that includes gravity is supergravity in D=11 dimensions with 4-space-time and compact 7-manifold.

As known, when strings are compactified, they have a fascinating extra property because can wind around a compact dimension. A closed string can wind around a periodic dimension an integral number of times with a momentum which goes as $p = wR,\ (w = 0,1,2,\ldots)$. As the compact dimension becomes small these winding modes becomes light. When n dimensions are compactified into circles, this is called toroidal compactification, because the product of n copies of a circle is an n-torus.

These general models all have in common that the spacetime is a direct product

$$E^{4+d} = M^4 \times X^d,$$

where M^4 is the four-dimensional noncompact spacetime, and X^d is d-dimensional compact internal space of characteristic size R. This means that the metric on M^4 doesn't depend on the coordinates in the internal space. The metric of the direct product space with $\mu = 0,1,2,3$ and $m = 1,2,\ldots,d$ is

$$ds^2 = G_{MN}(x)dx^M dx^N = g_{\mu\nu}(x)dx^\mu dx^\nu + \gamma_{mn}(x,y)dy^m dy^n.$$

In this case, the gravitational coupling constant as Newton's constant G_N in (4+d) dimensions of the superstring theory is given by

$$G_N = G_4 = G_{10}/V_X,$$

$V_X \sim R^d$ is the volume of the space of extra dimensions. In terms of the Planck mass M_{Pl}, $M_{Pl} = (G_4)^{-1/2} = 1.2\cdot 10^{19}$ GeV this relationship becomes

$$M_{Pl}^2 = V_X M^{d+2},$$

the mass M is the fundamental mass scale of the full n-dimensional theory. A consequence of these assumptions is that the effective *4d* scale is related to the fundamental Planck scale of the *(4+n)*-dimensional theory. It was the first extra dimensional models, the large extra dimensions scenario of Arkani-Hamed, Dvali, and Dimopoulos (ADD) [2] in which the compactified dimensions can be of macroscopic size, and they are referred to as “large extra dimensions” (LED) models.

If the space of extra dimensions is the d-dimensional torus, we’ll consider the linear deviation of the metric around the *(4 + d)*-dimensional η_{MN}

$$G_{MN}(x,y) = \eta_{MN} + \frac{2}{M^{1+d/2}} h_{MN}(x,y)$$

with $h_{MN}(x,y) = \sum_n h_{MN}^{(n)}(x)\frac{1}{\sqrt{V_{(d)}}}e^{-i\frac{n_m y^m}{n}}$

The masses of KK particles are

$$m_n = \frac{1}{R}\sqrt{n_1^2 + n_2^2 + \ldots + n_d^2} \equiv \frac{|n|}{R},$$

The Newton potential between masses m_1 and m_2 is given by

$$V(r) = G_{N(4)}m_1 m_2 \sum_n \frac{1}{r}e^{-m_n r} = G_{N(4)}m_1 m_2\left(\frac{1}{r} + \sum_{n\neq 0}\frac{1}{r}e^{-|n|r/R}\right)$$

with contribution of massless graviton (first part) and massive gravitons in the second part of this expression. It is necessary to stress, that within this model were analyzed decays of the graviton KK-modes into the SM particles [3], that will be considered later in our paper.

As is known from [4] the $E_8 \times E_8$ heterotic string can be identified with the 11-dimensional M-theory with one additional dimension compactified to the S^1/Z_2 orbifold with the corresponding set of E_8 gauge fields. By compactifying this theory on the Calabi-Yau manifold one arrives at a theory which, behaves like a 5D N = 1 supersymmetric (SUSY) model with one dimension compactified on S^1/Z_2. The effective action of this theory was derived in [5].

The metric of the theory is the following

$$ds_{11}^2 = \eta_{\mu\nu}(x)dx^\mu dx^\nu - R_0^2(dx^{11})^2 . - V_0^{1/3}\Omega_{AB}dx^A dx^B$$

with four-dimensional indices $\mu, \nu, \rho, \ldots = 0,1,2,3$, indices *A,B,C, • • • = 4, • • • 9* for the Calabi–Yau space, Ω_{AB} is a Calabi–Yau metric and moduli V_0 , R_0 are the Calabi–Yau volume and the orbifold radius, respectively.

In the Kaluza-Klein picture, the extra dimensions are rolled up in compact space with a very small volume, with massive states called Kaluza-Klein particles.

The braneworld scenario relies on allowing the extra dimensions to be noncompact, but with a warped metric that depends on the extra dimensions. In 5-**dimensional warped geometry theory** our universe is presented as a five-dimensional anti-de Sitter space with the elementary particles localized on a (3 + 1)-dimensional brane and graviton localized in fifth extra dimension, see Fig. 1. (URL: https://inspirehep.net/record/1082990/plots).

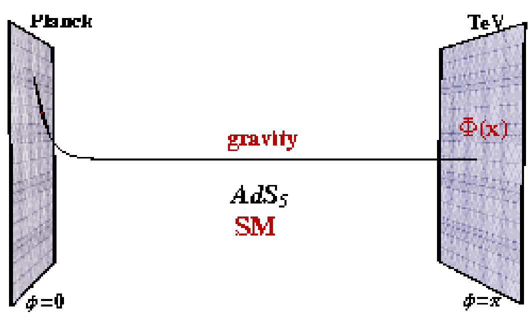


Fig. 1. Setup of the minimal Randall-Sundrum model

The Randall-Sundrum model (RS1) with metric in five spacetime dimensions

$$ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c d\phi^2$$
$$\phi \approx -\phi, \ |\phi| \le \pi$$

The three-dimensional space that is a three-dimensional subspace, called a 3-brane, located at $\phi = 0$, with another 3-brane located at $\phi = \pi$. The full four-dimensional space, or five-dimensional spacetime, is the bulk. Since the extra space dimension is noncompact and the law of gravity changed, the graviton falls away in the direction of the extra dimension. This model is rather perspective describing spectra of KK partners of the graviton and the vector boson in five-dimensional space-time with nonfactorizable geometry [6].

It solves the problem of the hierarchy, t. e. connects two different energy scale (the Planck scale $M_{Pl} = 10^{19}$ GeV and the TeV scale $M = 10^4$ GeV) using the formula

$$M_{Pl}^2 = \frac{M^3}{k}\left(1 - e^{-2kr_c\pi}\right),$$

where $k = 10^3$ GeV and $R = 10^{-17}$ cm determine the size of extra dimensions and therefore, the processes going on at the Planck energy, should be observed at the Large Hadron Collider (LHC).

One of the interesting models of extra dimensions that used in the paper is TeV^{-1} sized extra dimension model, which arises in braneworld theories [7].

The considered theoretical models of gravity and particle physics before they can make predictions of new physics they should not contradict any existing theoretical or experimental knowledge. In superstring theory with Kaluza-Klein compactification, there are several different energy scales in going from a string theory to a low energy effective particle theory that is consistent with observed particle physics and cosmology. The attribute of superstring theory is its possible experimental detection. Supersymmetry breaking and compactification of higher dimensions have to give the low energy physics observed in accelerators.

The ideology of the presented models will be used throughout the article.

2. COMPUTER MODELING OF PRODUCTION CROSS SECTIONS FOR KK GRAVITONS AND VECTOR BOSONS

Heavy resonances are predicted by several models beyond the Standard Model. Three models of extra dimensions are considered in our paper: RS1 model, TeV^{-1} model and LED.

For five-dimensional metric of gravity of RS1 model KK-masses are determined by formula $M_n^{G,A} = \beta_n^{G,A} k$. For k = 1 TeV the masses of KK gravitons take the values 3.83; 7.02; 10.17; 13.32;… TeV and the masses of vector bosons are 2.40; 5.52; 8.65; 11.79;… TeV [8].

In [9] was performed computer modeling of KK parameters for the graviton (Fig. 2).

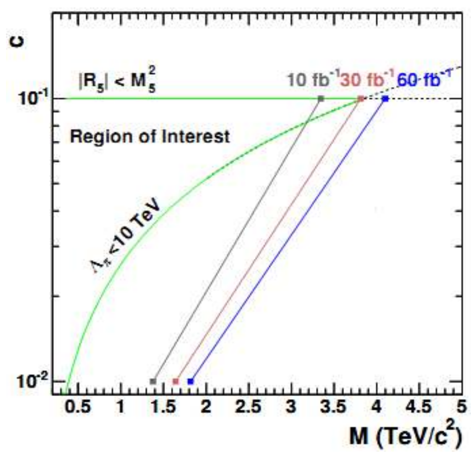


Fig. 2. Five σ discovery plane for graviton production as a function of the coupling parameter c and the graviton mass from [9]

So, for coupling parameter c= k/M =0.1 we can receive mass of graviton about 3.8 TeV, that agree with the calculations of graviton spectra. This coupling parameter will be used for the further calculations of the KK-particles production cross sections.

Using the computer program PYTHIA8.2 [10] we calculated the production cross section of graviton KK-modes as function of energy at the LHC, presented in Fig. 3.

It is seen the increase of the production cross section with the growth of the center of mass energy at the LHC. We have considered only two processes of graviton KK-modes gluon-gluon ($gg \to G^*$) and fermion-antifermion ($f\bar{f} \to G^*$) as the most important.

It was interesting to consider possible resonances corresponding to c=0.1 for KK gravitons of the RS1 model. Fig. 4 presents the results of our calculations for KK graviton production cross sections in the energy scale 10-11 TeV.

Gaussian distribution in the M=10.5 TeV is consistent with previously calculated result for mass of RS1 KK graviton M=10.17 TeV.

In Fig. 5 presented results for KK graviton production cross sections in the energy scale 12-14 TeV.

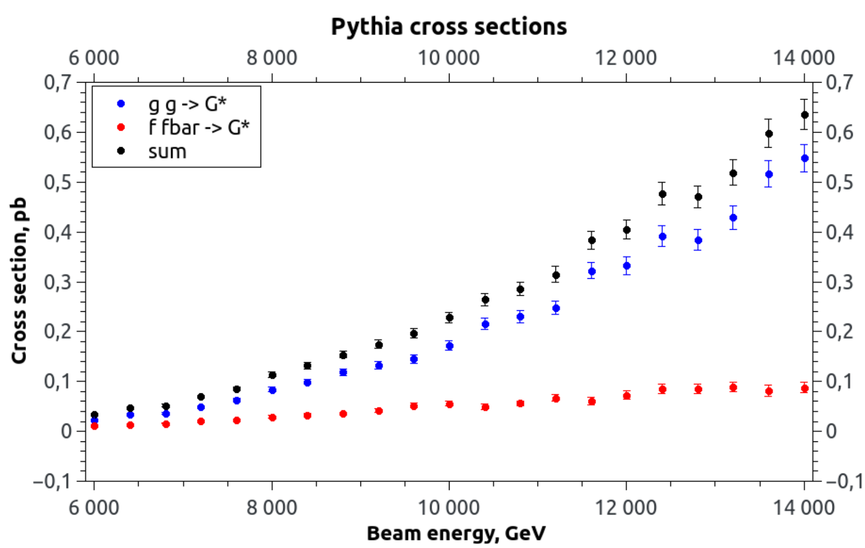


Fig. 3. Production cross section of graviton KK-modes as function of energy at the LHC in the RS1 model

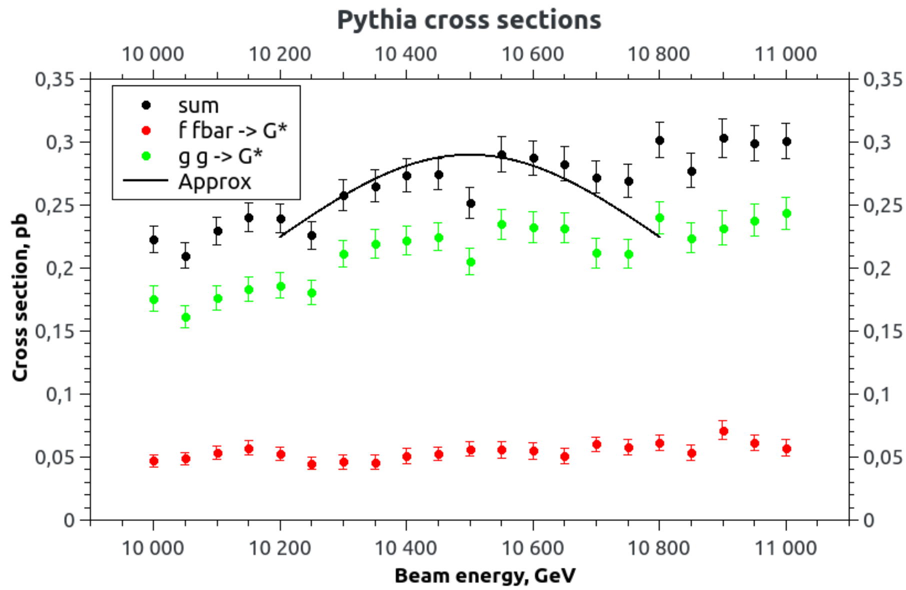


Fig. 4. KK graviton production cross sections in the energy scale 10-11 TeV at the LHC in the RS1 model

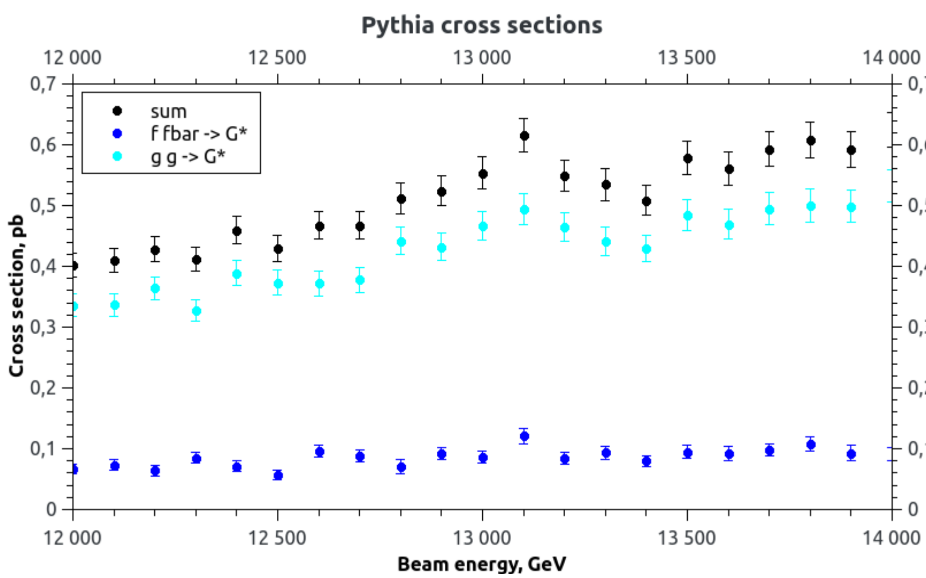


Fig. 5. KK graviton production cross sections in the energy scale 12-14 TeV at the LHC in the RS1 model

The resonance in the M=13.1 TeV is consistent with calculated result for mass of RS1 KK graviton M=13.32 TeV.

With the help of computer program PYTHIA8.2 [10] we have calculated the production cross section of vector boson KK-modes as function of energy in the cms at the LHC, presented in Fig. 6.

We have used TeV^{-1} sized extra dimension model. According to this model, the Standard Model fermions are confined to the brane but the gauge fields of the SM exist in the bulk.

It was important to consider the processes $f\bar{f} \to \nu_\mu \bar{\nu}_\mu$, $f\bar{f} \to \mu^+\mu^-$, $f\bar{f} \to e^+e^-$, $f\bar{f} \to t\bar{t}$ with pure Z_{KK} contribution, n=10 and

M_c=4 TeV. From Fig. 6 could be seen the lepton flavor symmetry and predominance of the $t\bar{t}$ production. Moreover, production cross section of KK vector boson an order of magnitude less than KK graviton production cross section.

The masses of the gauge bosons in the extra dimensions of TeV^{-1} model are equivalent to towers of KK states with masses described by $m_n = \sqrt{M_0^2 - n^2 M_c^2}$, with M_0 the mass of the SM gauge boson, M_c – compactification scale and the number of KK-modes n=1,2,…. From this expression for mass it would be interesting to see the possible resonances of this model, presented in Fig. 7.

It can be seen from Fig. 7, that resonances for KK vector boson masses $m_1 \approx 5500$ GeV and $m_1 \approx 11790$ GeV are manifested weakly and the magnitude of production cross sections for KK vector bosons with the selected parameters is much smaller (two orders (a) and three orders (b) of magnitude) than the production cross sections of Fig. 6. So, it was of interest to calculate the dependence of the production cross section on the KK vector boson masses with the LHC energy 14 TeV, presented in Fig. 8.

It can be seen from Fig. 8 the difference of the cross sections for the KK vector boson with n=1 and n=10 in narrow mass range 2-4 TeV, where the result for n=10 exceeds the result for n=1. In other mass range these calculations are practically coincide.

As was noticed above, KK graviton falls away in the direction of the extra dimension, so the searches for new heavy resonances are possible only through the decays into the particles of SM. The lepton decay channels of KK-modes provide a clean signature at the LHC (CMS and ATLAS). So we calculated with the help of PYTHIA8.2 the production cross section for the following LED processes with virtual graviton exchange:

- $f\bar{f} \to (LED\ G^*) \to \gamma\gamma$
- $gg \to (LED\ G^*) \to \gamma\gamma$
- $f\bar{f} \to (LED\ G^*) \to ll$
- $gg \to (LED\ G^*) \to ll$.

The results are presented in Fig. 9.

From these Fig. 9 we see the dominance of the gluon-gluon fusion over the results for fermion – antifermion fusion in the same final decay channels. The increase of cross section with energy is a natural.

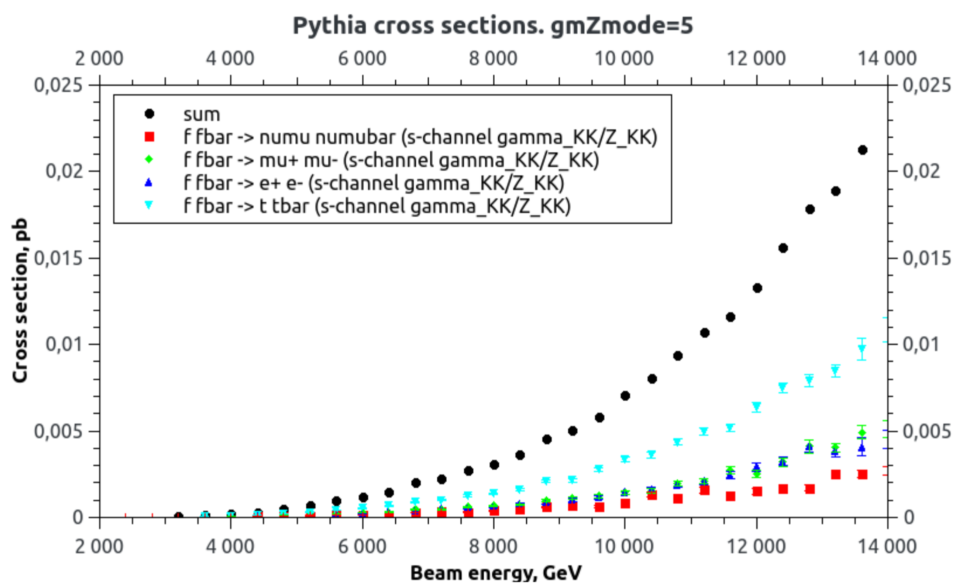
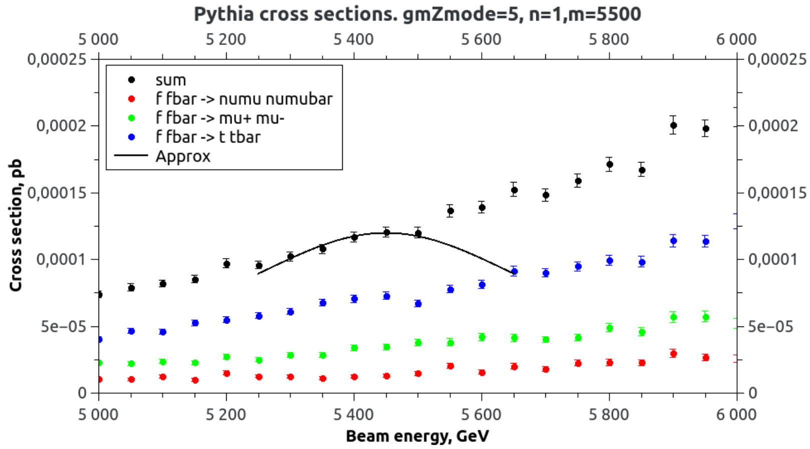
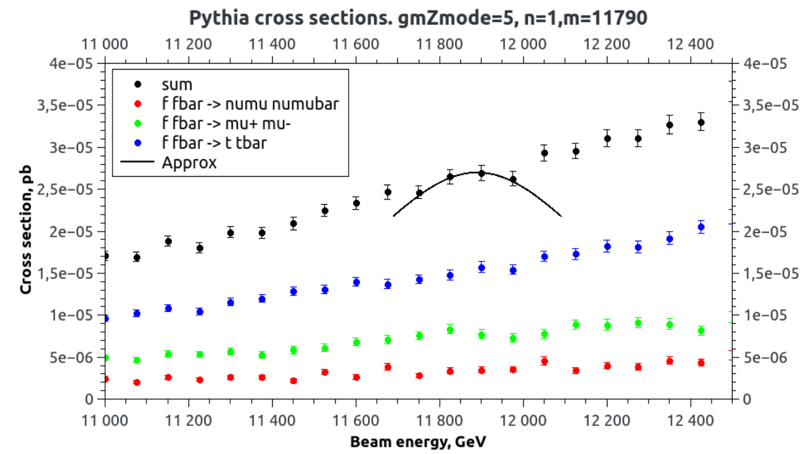


Fig. 6. Production cross section of KK vector boson as function of energy at the LHC with n=10 and M_c=4 TeV in the TeV^{-1} model



a)



b)

Fig. 7. KK vector boson production cross sections in the energy scale a) 5-6 TeV with parameters n =1, M_c=5.5 TeV b) 11-12.4 TeV with parameters n=1, M_c=11.79 TeV in the TeV^{-1} model

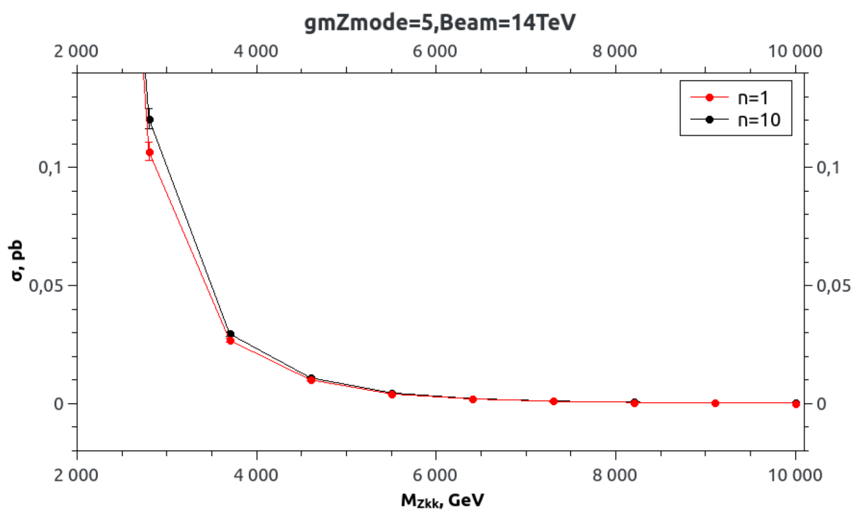


Fig. 8. The production cross section for the KK vector boson in the TeV-1 model

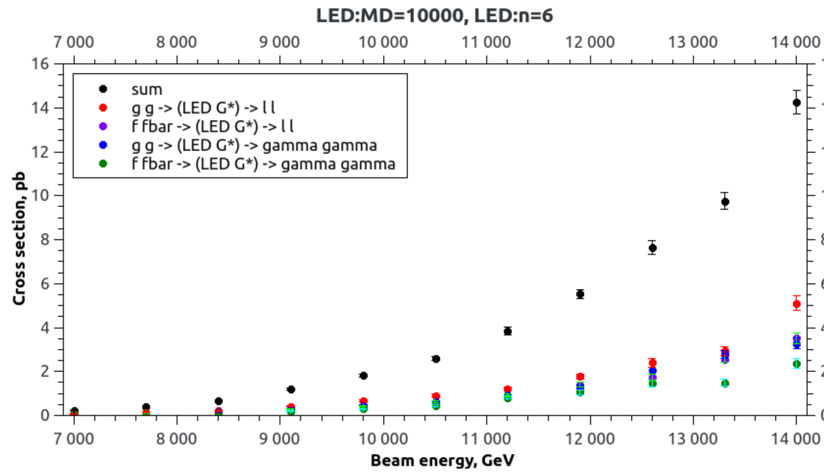


Fig. 9. The production cross section for the four LED processes with virtual graviton exchange

3. COMPARISON OF COMPUTER MODELING DATA WITH THE LATEST EXPERIMENTAL SEARCHES FOR KK GAUGE BOSONS

Let's consider the latest experimental data focused on heavy gauge bosons searches performed by the ATLAS and CMS experiments. Heavy gauge bosons, which refer to heavier versions of the weak gauge bosons are predicted in several classes of theories, the most studied of which is the sequential standard model (SSM) [11]. The resulting limit on the cross section times branching ratio for a SSM Z0 dependent on the resonance mass is shown in Fig. 10.

Experiment report observed limits of 2.9 TeV on the Z0 SSM mass. As this results may be reinterpreted for any model, we can compare it with the character of the production cross section for the KK vector boson in the TeV-1 model of Fig. 8. It shows that the observed limit of TeV-1 model on the Z0 mass is larger than 2.9 TeV.

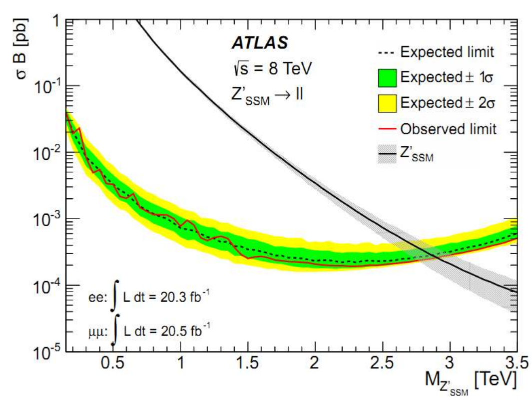


Fig. 10. 95% CL limits on the cross section × branching ratio dependent on the resonance mass for the ATLAS [12] searches from [13]

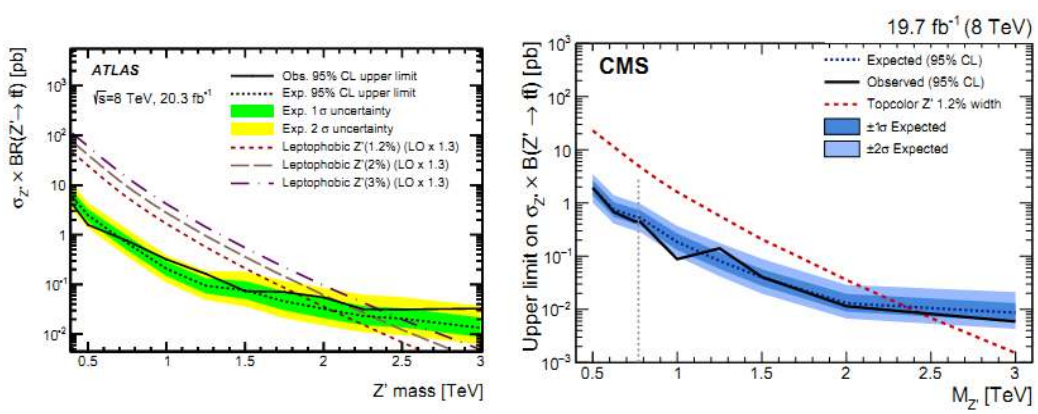


Fig. 11. 95% CL exclusion limits on the branching ratio × cross section dependent on the Z_0 mass for ATLAS [14] (left) and CMS [15] (right) from [13]

As ATLAS and CMS found lower limits of 1.8TeV and 2.4TeV with a width of 1.2% and 1% of the Z0 mass respectively (Fig. 11), the searches for heavier KK resonances are still relevant.

It was stressed in [13] that $t\bar{t}$ final states are the most promising channel to probe the production of Kaluza-Klein modes at the LHC.

This fact emphasizes the importance of selecting $t\bar{t}$ channel in the calculation of KK vector boson production cross section of TeV^{-1} model.

4. CONCLUSION

Within the RS1, TeV^{-1} and LED models of extra dimensions was performed the computer modeling of production cross sections for gravitons and Z bosons KK modes. For KK graviton were found resonances about 10.5 TeV and 13.1 TeV according to RS1 model. It can be seen that RS gravitons are produced with a significant cross section from gluons in the initial state ($gg \to G^*$). The same searches for the KK resonances of vector bosons were carried out in TeV^{-1} model. No significant results for the resonances in the predicted theoretical range of masses were found. It is important to note the larger value of KK modes production cross sections in $t\bar{t}$ channel compared to other lepton channels in TeV^{-1} model. The calculated production cross sections for the four LED processes with virtual graviton exchange show the predominance of the lepton decay channel from gluons of the initial state. Moreover, it is necessary to emphasize the advantage of the gluon-gluon and $t\bar{t}$ channels for searches of KK-modes. It was carried out the comparison of calculated KK Z boson masses with the ATLAS and CMS searches for the KK vector bosons. As no significant evidence for physics beyond the standard model was found, the presented analysis is connected with lower limits on KK Z boson masses. The restart of the LHC at the center of mass energy of 14 TeV will increase the discovery reach for most theories including the theories of extra dimensions.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Castellani L, Auria D', Fre P. Supergravity and Superstrings: A geometric perspective. World Scientific, Singapore. 1991;2.
2. Arkani-Hamed N, Dimopoulos S, Dvali GR. The hierarchy problem and new dimensions at a millimeter. Phys. Lett. 1998;B429:263–272. arXiv: hep-ph/9803315.
3. Kubyshin Yuri A. Models with extra dimensions and their phenomenology. E-print arXiv: hep-ph/0111027.
4. Horava P, Witten Heterotic E. Type I string dynamics from eleven dimensions. Nucl. Phys. 1996;B460:506-524;

   Horava P, Witten E. Eleven-dimensional supergravity on a manifold with boundary. Nucl Phys. 1996;B475:94-114.
5. Lukas A, Ovrut BA, Stelle KS, Waldram D. The universe as a domain wall. E-print arXiv: hep-th/9803235.
6. Randall L, Sundrum R. A large mass hierarchy from a small extra dimension. E-print arXiv: hep-ph/9905221.

   Pomarol A. Gauge bosons in a five-dimensional theory with localized gravity. E-print arXiv: hep-ph/9911294.
7. Antoniadis I. A possible new dimension at a few TeV, Phys. Lett. 1990;B246:377–384.
8. Malyuta Yu, Obikhod T. New physics beyond the standard model. Reports of National Academy of Sciences of Ukraine. 2007;№9:59-61.
9. CMS Technical Design Report. CERN-LHCC. 2006;2:021.
10. Sjöstrand T, et al. An Introduction to PYTHIA 8.2. Comput. Phys. Commun. 2015;191:159-177.
11. Altarelli G, Mele B, Ruiz-Altaba M. Searching for new heavy vector bosons in pp colliders Z. Phys. 1989;C45:109-121.
12. ATLAS Collaboration. Search for high-mass dilepton resonances in pp collisions at sqrt(s) = 8 TeV with the ATLAS detector. Phys. Rev. 2014;D90(5):052005.
13. Pook T. Extra dimension-inspired models: Z', W', dijet resonances, black hole searches. E-print arXiv:1512.02371 [hep-ex].

14. ATLAS Collaboration. A search for tt resonances using lepton-plus-jets events in proton-proton collisions at s√=8 TeV with the ATLAS detector. E-print arXiv:1505.07018 [hep-ex].

15. CMS Collaboration. Search for resonant ttbar production in proton-proton collisions at sqrt(s) = 8 TeV. E-print arXiv: 1506.03062 [hep-ex].

Peer-review history:
The peer review history for this paper can be accessed here:
http://sciencedomain.org/review-history/15740