Dilepton + jet signature of Split-UED at the LHC

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Abstract: We study the signature of dilepton and a hard jet (ℓ⁺ℓ⁻j) via heavy new gauge boson production in split universal extra dimension scenario where the Kaluza-Klein parity is conserved but the Kaluza-Klein number is not. A hard cut to the jet energy effectively removes virtually all possible backgrounds and provides a handle to search of new physics involving new neutral heavy states as the Kaluza-Klein Z boson. The signature can be more generically used in search of other new states such as graviton and radion in warped extra dimension models.
1 Introduction

The robustness of the Standard Model (SM) of particle physics become even more clearer as the CERN Large Hadron Collider (LHC) experiment continued to have more data. The LHC should be already regarded as a successful experiment with its recent discovery of the Higgs boson. In its long time run, however, it aims besides Higgs boson search to explore new physics beyond the standard model. It is extremely important now to have some strategy to cover a wide range of new physics models but still have reasonably good handles to discriminate new physics signatures from the standard model backgrounds.

We think that the signature with dilepton plus a hard jet ($\ell^+\ell^-j$) can provide a good chance to probe new physics models with a new heavy (bosonic) state, $Z'$, beyond the standard $Z$-boson, for which putting a rather high cut in the jet energy can efficiently remove the SM background mainly coming from the $Z$-boson contributions. The heavy neutral state, $Z'$, can be found in many new physics models such as models with extended gauge sectors (e.g., LR-model [1–4], Little Higgs model [5]) and/or more spacetime dimensions and even with heavy gravitational sectors (e.g., ADD [6–8], RS [9, 10], UED [11] models). Having such a large variety, the expected collider phenomenology would also vary differently with the details of the setups but still some typical collider signatures can be studied provided that the mass of $Z'$ is in the reach of the LHC ($m_{Z'} \lesssim 5$ TeV) and the coupling with the SM quarks and leptons is sizable. Hereafter, we would focus on $Z'$ in extra dimension models as an explicit example but the analysis can be applicable many different models too.

The extra dimensional models where the particles can access more extra space dimension than usual (3 + 1) space-time world, are quite promising as they can address several pressing problems in the SM. The phenomenological introduction of the extra-dimensional model was motivated to explain the well known hierarchy problem [12–15] allowing gravity only to access some flat [6–8] or curved [9, 10] space-time extra-dimensions. There are a few variations of these models depending on whether gravity only, or gauge bosons only or
some other combinations of SM members are allowed to access the extra dimensions. In this direction Universal Extra Dimension (UED) is quite unique [11] due to the fact that all the SM-particles can access these new space dimensions.

In case of minimal UED (MUED) the extra space dimension is to be compactified on an $S^1/Z_2$ orbifold or equivalently on an interval, needed to have a chiral fermion at the zeroth level. Due to this orbifolding momentum along the fifth dimension, and hence the KK number, is no more conserved but a $Z_2$-inversion symmetry about the middle point of the extra dimension, similar to R-symmetry in Minimal Supersymmetric Standard Model (MSSM), called $KK$-parity remains there. At the tree level, many production channels are restricted what allow to bring down the $R^{-1}$ up to a few hundred GeV. The model has a few good phenomenological implications, like, could be a natural source of dark matter particle [16–20], can give a TeV scale Grand Unified Theory [21–24], modify the supersymmetric Higgs boson mass [25], and can be successfully explored at the CERN LHC [26–42].

**Figure 1.** Schematic diagram of jet + dilepton production.

Because of its structural virtue all the SM fermions in this model can have some vector like bulk mass terms, which is considered to be zero. However this bulk mass term is naturally included in split-UED scenario [18, 43–46]. This mass term has a great impact on the coupling and mass spectra, will be discussed in the next section, and the phonomenology is much different than the MUED case. One interesting feature is that now we could have a KK-number violating coupling at the tree level. As a matter of fact, second KK-level weak gauge bosons can directly decay into a pair of light fermions without any missing energy – the scenario is absent in MUED, R-parity conserving MSSM or any other new physics

**Figure 2.** RS model can give a similar final state, where Graviton will decay into two leptons.
containing a $Z_2$-symmetry. We thus consider here this distinct channel $pp \rightarrow j\ell^+\ell^-$, as shown in Fig. 1 to probe split-UED at LHC. However, a single jet associated with dilepton final state may also appear in some other new physics areas like RS-model etc where, as shown in Fig. 2, the dileptons are produced from the decay mode of the Graviton, radion or some other particles. LHC has now reached to an energy scale either to discover or turned down many new physics scenarios. At this energy scale it produce quite high energetic multiple number jets with hard leptons. ATLAS [47] and CMS [48] discuss the channel of $Z$ plus jets as a final state to test perturbative QCD. It is thus timely to have a look at some new physics in this directions. Here, we consider the split-UED scenario. We admit that the analysis we put here is at the parton level and so a further detail analysis should be performed.

Collider signature of split-UED for different channel, where dilpetons are produced in $s-channel$ mediated by the $Z_2$ or $\gamma_2$ has already been studied in ref. [18, 43, 49]. However, in this study we have a real production of the second KK-excited mode of the weak gauge bosons associated with a jet. The final state is different than the previous analysis. In this case, the jet will be produced back-to-back with the heavy excited gauge boson which will decay into two leptons. Thus, all the final state particles, the jet and two leptons, have large momentum. Due to this feature of a single hard jet and two hard leptons we can easily use a strong cut to make our final states free from any standard model background. The analysis can probe up to a few TeV of $Z_2$ mass of the model with 100 fb$^{-1}$ luminosity at the LHC.

This paper is organised as follows. Briefly introducing the physics for split-Universal Extra Dimension in the next section we will write down the possible wave function expansion of various gauge and fermion fields in this model. In the next section, we then estimate the possible mass spectra and their various branching ratios for the related particles in our model. We then discuss the production of the second KK-mode of weak gauge bosons, which would decay either to zero mode quarks or leptons, associated with a zero mode quark. With the proper cut used here in this analysis, our jet + dilepton final states will be free from any sizable standard model background. We make our conclusion in the last section.

2 split-UED review

In split-UED the full spacetime, $x^M = (x^0, x^1, x^2, x^3, y)$, include an extra dimension compactified on an $S^1/Z_2$ orbifold, with a radius $R$. The orbifold can be regarded as an flat interval $[-L, L] = [-\pi R/2, \pi R/2]$ where the end points $y = \pm L$ correspond to the fixed points of the orbifold. All the SM fields, gauge bosons, Higgs and fermions, are in the full spacetime so that each of them can be decomposed into KK-states with a finite mass gap, $\Delta m \sim 1/R$. The zero modes are identified with the SM field in the end.

One of the most interesting features of split-UED is the bulk mass terms for fermions. Indeed, the spinor in five dimensions includes both chiralities in four dimensional sense, so that it can have Dirac mass term, which is consistent with five dimensional Lorentz
symmetry as well as gauge symmetries:

\[ L_{\text{split-UED}} = L_{\text{MUED}} + \int_{-L}^{L} dy \sum_{\Psi} [M_{\Psi}(y) \overline{\Psi}(x^\mu, y) \Psi(x^\mu, y) + \text{h.c.}], \]

(2.1)

where \( \Psi(x^\mu, y) = \{Q, U^c, D^c, L, E^c\} \) denote the bulk fermion fields for quarks and leptons and \( M_{\Psi}(y) = -M_{\Psi}(-y) \) is introduced to keep the KK-parity under which the spinor field transforms as \( \Psi(y) \to -\Psi(-y) \). The bulk mass terms do not contribute to the masses for zero mode fermions, i.e., the SM fermions, but control the wave function profiles of each fermion along the extra dimension so that its interaction patterns with the KK gauge bosons could be modified.

Here we simply collect some informations on KK masses and couplings in split-UED for our phenomenological study (the details of split-UED could be found in original Ref. e.g., [49]):

- We are mostly interested in the KK-gauge boson couplings with the zero mode leptons and quarks, which can be obtained by

\[ g_{Z_n \ell_0 \bar{\ell}_0} = g_5 D \int_{-L}^{L} dy f_{W_n \ell_0 \ell_0} \equiv g_{\text{SM}} F_{00}^n(\mu_L), \]

\[ g_{Z_n q_0 \bar{q}_0} = g_5 D \int_{-L}^{L} dy f_{W_n q_0 \bar{q}_0} \equiv g_{\text{SM}} F_{00}^n(\mu_q), \]

(2.2)

where \( f_{\ell_0} \) and \( f_{q_0} \) are the zero mode wave functions for the quark and lepton. The Standard Model couplings could be obtained by \( g_{\text{SM}} = g_5 / \sqrt{2L} \). The 5D bulk mass parameters \( \mu_q \) and \( \mu_L \) are for quark and lepton, respectively.

- Thanks to the KK-parity conservation, only KK-even modes have non-zero couplings.

\[ F_{00}^{2n}(x) = \frac{x^2 [1 - (-1)^n e^{2x}] [1 - \coth(x)]}{\sqrt{2(1 + \delta_{0n}) [x^2 + n^2 \pi^2/4]}. \]

(2.3)

- The mass for the KK-Z-boson in split-UED is the same as in minimal-UED as there is no mass term allowed due to gauge symmetry:

\[ m_{Z(n)} = \sqrt{m_Z^2 + \frac{\pi^2 n^2}{4L^2}}, \text{ (split-UED)} \]

(2.4)

where \( m_Z = 91.1876 \pm 0.0021 \text{ GeV} \) [50] and the KK-number is positive integer, \( n \in \mathbb{Z}^+ \).

- The KK mass for fermions in split-UED is

\[ m_{f(n)} = \sqrt{m_f^2 + \mu^2 + k_n^2}, \text{ (split-UED)} \]

(2.5)

where \( m_f = \lambda_f v \) is the mass obtained through Yukawa interaction and the Higgs vev. The ‘fifth-momentum’ \( k_n \) is given as
3 Collider physics

3.1 Branching ratios

In this paper we are interested to look into the production and decay channel of the second KK-excited weak neutral gauge bosons $Z_2$ and $\gamma_2$ associated with high energetic jet. Mixing of this heavy gauge bosons with the corresponding zero modes are almost zero, so the $\gamma_2$ is just the second KK excited mode of the $B$-boson while $Z_2$ the corresponding excited mode of the third component of the $W$-boson. The branching fractions certainly depend on the bulk mass parameter $\mu$. A very small bulk mass term, $|\mu| << 1$, the phenomenology would be similar as in UED, so we briefly mention here the possible branching ratios for the two heavy weak gauge bosons, $\gamma_2$ and $Z_2$ for the region where $|\mu| \sim 0.5$. To discuss this, we consider three different cases – where the bulk mass parameter is universal to both quarks and leptons and two other situations in which either quarks or leptons have zero bulk mass. In this case, we do have tree level coupling, stronger than the SM coupling constant, of $\gamma_2$ and $Z_2$ decaying into fermion pair, which is suppressed by the loop level in MUED case. The decay widths for the $\gamma_2$ and $Z_2$ decaying into a pair of the SM fermion final states are roughly given by $\Gamma \sim \frac{M_{\gamma_2/Z_2}^3}{8\pi}(g_L^2 + g_R^2)$, where couplings $g_L$ and $g_R$ are discussed below.

As the fermions get more radiative correction than $\gamma_n$, so for $n = 2$ its decay into either two first KK-mode fermion pair or a combination of a zero mode fermion and second KK-mode of fermion is kinematically not allowed. Thus this $\gamma_2$ state would completely decay into a pair of standard fermion-antifermion. In the case of the universal bulk mass term for all the quarks and leptons, the $\gamma_2 - f_0 - \bar{f}_0$ coupling $g_L/R$ is completely governed by the corresponding hypercharge quantum number of the associated fermion and proportional to the $U(1)$ coupling constant. The branching ratio thus one can easily read, as given in Table-1 36.7% for the dijet, 4.15% for the $b\bar{b}$, 36.7% for the $t\bar{t}$ and 25% for the dilepton, 12.5% for $\tau \bar{\tau}$ and the rest 7.5% into neutrino as missing energy.

In case of $Z_2$, the gauge boson get some radiative corrections and to give the branching ratios we will reiterate what is discussed before in ref [49]. This radiative correction and the zero mode electroweak mass makes $Z_2$ as heavy as roughly around 1.07 times that of the $\gamma_2$ mass [51, 52]. However, although the second excited state of different fermions do not receive much corrections from the bulk mass but the corresponding coupling constants $Z_2 - f_0 - f_2$ are highly suppressed for a large value of $\mu$, and the same is also true for the $Z_2 - f_1 - f_1$ coupling constant. Thus, the only dominant decay mode left is decaying into a pair of SM fermions. As $Z_2$ is basically $W_3$, the corresponding decay mode is simply the weak coupling constants and hence $Z_2$ would decay into left-handed particles only. For a
universal bulk mass parameter, \( Z_2 \) dominantly decay into dijet 50\% and 12.5\% into both \( b\bar{b} \) and \( t\bar{t} \) while 8.3\% into dilepton, 4.2\% into \( \tau\bar{\tau} \) and 12.5\% into missing energies.

Since the \( Z_2 \) and \( \gamma_2 \) couplings with the fermion pair solely depend on the \( \mu \)-parameters, the corresponding leptons and quarks channels are off once we consider the vanishing \( \mu_q \) and \( \mu_l \) respectively.

In the limit \( \mu_q = 0 \) where vector bosons now only decay into the leptonic final states the branching ratio for the \( \gamma_2 \) decay mode is thus given as 55.6\% into dilepton, 27.7\% into \( \tau\bar{\tau} \) pair and the rest 16.7\% into missing energies while the same for the \( Z_2 \) are respectively given 33.3\%, 16.7\% and 50\%. On the other hand, In the limit \( \mu_q = 0 \), both \( Z_2 \) and \( \gamma_2 \) decay into dijet with 66.7\% branching ratio while the same for the decay mode into \( b\bar{b} \) and \( t\bar{t} \) pair is 16.65\% each. The branching ratios for the \( \gamma_2 \) decay into \( b\bar{b} \) and \( t\bar{t} \) pair are respectively given by 7.5\% and 25.8\%, as shown in Table-1. As we can see the branching ratios are varying in these two different scenarios, so the corresponding collider phenomenology will be highly effected. This will be discussed elsewhere in future analysis.

| Decay Channel | Branching Ratios (in %) |
|---------------|-------------------------|
|               | \( \mu_q = \mu_l \) | \( \mu_q = 0 \) | \( \mu_l = 0 \) |
| \( Z_2 \to f\bar{f} \) | 50 | 36.7 | 0 |
| \( \gamma_2 \to f\bar{f} \) | 0 | 0 | 66.7 |
| \( b\bar{b} \) | 12.5 | 4.15 | 0 |
| \( t\bar{t} \) | 12.5 | 14.15 | 0 |
| dilepton | 8.3 | 25 | 33.3 |
| \( \tau\bar{\tau} \) | 4.2 | 12.5 | 16.7 |
| neutrinos | 12.5 | 7.5 | 50 |

Table 1. Branching ratios for the \( Z_2 \) and \( \gamma_2 \) decay modes into pair of light fermions.

### 3.2 Production and decay of heavy weak neutral gauge bosons

We will now consider the specific channel of one jet plus two leptons final state for the split-UED model. The main production channel is \( qg \to q^0Z^2 \) (or \( q^0\gamma^2 \)), where \( q^0 \) could be both doublet as well as singlet quark, as shown in Fig.-3. The corresponding \( s \)- and \( t \)-channel parton level matrix element square one can write as
\[ |\mathcal{M}(gg \rightarrow q^0 Z^2/\gamma^2)|^2 = \frac{\pi \alpha_s(\hat{s})}{3}(g_L^2 + g_R^2) \left[ \frac{\hat{s} \hat{t}}{\hat{s}^2} - \frac{\hat{s} \hat{t}}{\hat{t}^2} + \frac{2((\hat{s} + \hat{t})m_{Z^2/\gamma^2}^2 - m_{Z^2/\gamma^2}^4)}{\hat{s} \hat{t}} \right]. \]

(3.1)

In the above equation \( \hat{s} \) and \( \hat{t} \) are the parton level Mandelstam variables for the above processes while \( m_{Z^2/\gamma^2} \) representing the mass of the final state weak vector boson \( Z^2/\gamma^2 \). Since the mixing of the second KK-mode weak neutral gauge bosons \( Z^2/\gamma^2 \) with the corresponding zero-th mode states is almost negligible, as mentioned before \( Z^2 \) is basically the third component of the second KK-mode of the \( W \) boson while \( \gamma^2 \) is just the same of the \( B \)-boson. So, the coupling \( g_L \) is the only nonzero coupling for the left-handed fermions in case of production associated with the \( Z_2 \) boson. This is just the modified weak \( SU(2) \)-weak gauge coupling, as discussed in section-2. On the other hand, in case of \( \gamma^2 \) the couplings \( g_{L/R} \) will be proportional to the corresponding left/right hypercharge quantum number of the associated fermions times the modified \( g_Y \) coupling constant. In our analysis, we have used CTEQ6 parton distribution [53] with the renormalisation scale \( Q^2 = \hat{s} \) to calculate the parton level cross section at the LHC with center of mass \( \sqrt{s} \) equals to 14 TeV and 8 TeV. We have shown the variation of the total number of signal events for an integrated luminosity of 100 fb\(^{-1}\) with the inverse of compactification radius in Fig.-4. In this figure we have varied the bulk mass parameter \( \mu \) from 0.5 to 3.5, and we see the number of signal events increases with the increase of the bulk mass parameter, as the coupling constant increases while it decreases with the increase of the \( R^{-1} \) as the excited weak gauge bosons becoming heavier.

Since the zeroth mode quark will be produced along with a heavy gauge boson the jet will have a large momentum. In addition, these weak gauge bosons will directly decay into a pair of charged leptons so they would have large momentum as well. In this scenario we thus have a hard jet and two hard leptons and no missing energy. This is where the model differs from other new physics scenario, with an extra \( Z_2 \)-symmetry, where we can not have any tree level processes without contributing to missing energy. This high energetic jet and leptons allow us to use a strong cut on the \( p_T^{\text{jet}} \) and the dilepton invariant mass greater than 0.9 times the \( \gamma_2 \) mass. In addition, we have also used a rapidity cut \(|\eta| < 2.5\) for leptons and consider the leptons which are isolated from jet by \( \Delta R > 0.7 \) only. We

![Figure 3](image-url)  
Figure 3. Diagrams showing the production of a single jet + dilepton final state in split-UED model in s-channel (left) and in t-channel (right).
have used Madgraph [54] to estimate the SM background. The main channel which can contribute to a jet+ dilepton backgrounds are $t\bar{t}$, $b\bar{b}$, $t\bar{b}$ and $b\bar{t}$ processes. We can also have some background from the $Z\gamma^*$ processes or from a pair of Z-boson process. In either case the dilepton may arise from the decay of one Z-boson or $\gamma$. On the other hand another Z-boson will decay into a pair of jets. In case, they are close enough to fake as a single jet or only of the jet can have large momentum. However, the above strong cuts are good enough to wash out any of the mentioned background.

In Fig. 4, we have shown the variation of the required luminosity at LHC to have signal event with at least 95% confidence level, defined as $\sigma = \sqrt{S/(S+B)}$, with the $Z_2$ mass for a different set of values of the bulk mass parameters. We can see from the figure that our analysis can probe up to a few TeV of $Z_2$ mass with $\sim 100 \text{ fb}^{-1}$ luminosity at the LHC.

4 Conclusions

The Standard Model is almost complete with the discovery of the new boson at the LHC experiment. Beside some theoretical issues the signal is also not in complete agreement with what we expect from SM. These issues keep LHC to continue to its new physics search beyond the standard model. LHC has now reached to an energy scale and will continue to gear up more either to discover or turned down many new physics scenario. At this energy scale it produces quite high energetic multiple number jets with hard leptons. LHC has discussed the $Z$ plus jets as a final state to test different SM issues. It is thus timely to have a look at some of the new physics in this directions.
Figure 5. Luminosity required to have 95% signal over background at the LHC.

At the tree level a single jet plus dilepton may appear in a few new physics scenario, split-UED is one of such scenario. There is always a $Z_2$-like symmetry associated with most of the new physics, where a heavy stable particle is escape collider as missing energy. However, in split-UED the heavy weak neutral gauge bosons can directly decay into a pair leptons.

We consider in this paper the production of such a heavy weak gauge boson associated with a hard jet. Here our analysis is at the parton level and so a further detail analysis is much needed. As the heavy gauge boson will directly decay into a pair of leptons, they will have a very large momentum. This high energetic jet and leptons allow us to use a strong cut on the $p_T^{\text{jet}}$ and the dilepton invariant mass greater than 0.9 times the $\gamma_2$ mass. In addition, we have also used a rapidity cut $|\eta| < 2.5$ for leptons and consider the leptons which are isolated from jet by $\Delta R > 0.7$ only. We can have various SM channel to mimic our signal. However, the strong cut applied here can wash out any such background. Our analysis can probe up to a few TeV of heavy boson mass with a $\sim 100 \text{fb}^{-1}$ luminosity at LHC.

Acknowledgments

This work is supported by Basic Science Research Program through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology (2011-0010294) and (2011-0029758).
References

[1] J. C. Pati and A. Salam, *Lepton Number as the Fourth Color*, Phys. Rev. D **10** (1974) 275 [Erratum-ibid. D **11** (1975) 703].

[2] R. N. Mohapatra and J. C. Pati, *Left-Right Gauge Symmetry and an Isoconjugate Model of CP Violation*, Phys. Rev. D **11** (1975) 566.

[3] R. N. Mohapatra and J. C. Pati, *A Natural Left-Right Symmetry*, Phys. Rev. D **11** (1975) 2558.

[4] G. Senjanovic and R. N. Mohapatra, *Exact Left-Right Symmetry and Spontaneous Violation of Parity*, Phys. Rev. D **12** (1975) 1502.

[5] G. F. Giudice, C. Grojean, A. Pomarol and R. Rattazzi, *The Strongly-Interacting Light Higgs*, JHEP **0706** (2007) 045 [hep-ph/0703164].

[6] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, *The hierarchy problem and new dimensions at a millimeter*, Phys. Lett. B **429** (1998) 263 [arXiv:hep-ph/9803315];

[7] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, *New dimensions at a millimeter to a Fermi and superstrings at a TeV*, Phys. Lett. B **436** (1998) 257 [arXiv:hep-ph/9804398];

[8] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, *Phenomenology, astrophysics and cosmology of theories with sub-millimeter dimensions and TeV scale quantum gravity*, Phys. Rev. D **59** (1999) 086004 [arXiv:hep-ph/9807344].

[9] L. Randall and R. Sundrum, *An Alternative to compactification*, Phys. Rev. Lett. **83** (1999) 4690 [hep-th/9906064].

[10] L. Randall and R. Sundrum, *A Large mass hierarchy from a small extra dimension*, Phys. Rev. Lett. **83** (1999) 3370 [hep-ph/9905221].

[11] T. Appelquist, H. C. Cheng and B. A. Dobrescu, *Bounds on universal extra dimensions*, Phys. Rev. D **64** (2001) 035002 [arXiv:hep-ph/0012100].

[12] S. Weinberg, *Implications of Dynamical Symmetry Breaking*, Phys. Rev. D **13** (1976) 974.

[13] E. Gildener, *Gauge Symmetry Hierarchies*, Phys. Rev. D **14** (1976) 1667.

[14] L. Susskind, *Dynamics of Spontaneous Symmetry Breaking in the Weinberg-Salam Theory*, Phys. Rev. D **20** (1979) 2619.

[15] G. 't Hooft, *Recent Developments In Gauge Theories. Proceedings, Nato Advanced Study Institute*, Cargese, France, 1979 (Plenum, New York, 1980)

[16] G. Servant and T. M. P. Tait, *Is the lightest Kaluza-Klein particle a viable dark matter candidate?*, Nucl. Phys. B **650** (2003) 391 [arXiv:hep-ph/0206071].

[17] S. Matsumoto, J. Sato, M. Senami and M. Yamanaka, *Relic abundance of dark matter in universal extra dimension models with right-handed neutrinos*, Phys. Rev. D **76** (2007) 043528 [arXiv:0705.0934 [hep-ph]].

[18] S. C. Park and J. Shu, *Split Universal Extra Dimensions and Dark Matter*, Phys. Rev. D **79**, (2009) 091702.

[19] C. -R. Chen, M. M. Nojiri, S. C. Park and J. Shu, *Kaluza-Klein Dark Matter After Fermi*, arXiv:0908.4317 [hep-ph].
G. Belanger, M. Kakizaki and A. Pukhov, *Dark matter in UED: The Role of the second KK level*, JCAP 1102 (2011) 009 [arXiv:1012.2577 [hep-ph]].

K. R. Dienes, E. Dudas and T. Gherghetta, *Extra spacetime dimensions and unification*, Phys. Lett. B 436 (1998) 55 [arXiv:hep-ph/9803466].

K. R. Dienes, E. Dudas and T. Gherghetta, *Grand unification at intermediate mass scales through extra dimensions*, Nucl. Phys. B 537 (1999) 47 [hep-ph/9806292].

S. Hossenfelder, *Running coupling with minimal length*, Phys. Rev. D 70 (2004) 105003 [arXiv:hep-ph/0405127].

G. Bhattacharyya, A. Datta, S. K. Majee and A. Raychaudhuri, *Power law blitzkrieg in universal extra dimension scenario*, Nucl. Phys. B 760 (2007) 117 [arXiv:hep-ph/0608208].

G. Bhattacharyya, S. K. Majee and A. Raychaudhuri, *Extra-dimensional relaxation of the upper limit of the lightest supersymmetric neutral Higgs mass*, Nucl. Phys. B 793 (2008) 114 [arXiv:0705.3103 [hep-ph]].

C. Macesanu, C. D. McMullen and S. Nandi, *Collider implications of universal extra dimensions*, Phys. Rev. D 66 (2002) 015009 [hep-ph/0201300].

C. Macesanu, C. D. McMullen and S. Nandi, *New signal for universal extra dimensions*, Phys. Lett. B 546 (2002) 253 [hep-ph/0207269].

H. -C. Cheng, *Universal extra dimensions at the e^- e- colliders*, Int. J. Mod. Phys. A 18 (2003) 2779 [hep-ph/0206035].

A. Muck, A. Pilaftsis and R. Ruckl, *Probing minimal 5-D extensions of the standard model: From LEP to an e+ e- linear collider*, Nucl. Phys. B 687 (2004) 55 [hep-ph/0312186].

T. G. Rizzo, *Probes of universal extra dimensions at colliders*, Phys. Rev. D 64 (2001) 095010 [hep-ph/0106336].

G. Bhattacharyya, A. Datta, S. K. Majee and A. Raychaudhuri, *Exploring the Universal Extra Dimension at the LHC*, Nucl. Phys. B 821 (2009) 48 [arXiv:0904.0937 [hep-ph]].

D. Kim, Y. Oh and S. C. Park, *W' in new physics models at the LHC*, arXiv:1109.1870 [hep-ph].

T. Flacke, A. Menon and Z. Sullivan, *Constraints on UED from W' searches*, Phys. Rev. D 86 (2012) 093006 [arXiv:1207.4472 [hep-ph]].

A. Datta, K. Nishiwaki and S. Niyogi, *Non-minimal Universal Extra Dimensions: The Strongly Interacting Sector at the Large Hadron Collider* arXiv:1206.3987 [hep-ph].

A. Datta, U. K. Dey, A. Shaw and A. Raychaudhuri, *Universal Extra-Dimensional Models with Boundary Localized Kinetic Terms: Probing at the LHC*, arXiv:1205.4334 [hep-ph].

P. Bandyopadhyay, B. Bhattacharjee and A. Datta, *Search for Higgs bosons of the Universal Extra Dimensions at the Large Hadron Collider*, JHEP 1003 (2010) 048 [arXiv:0909.3108 [hep-ph]].

G. Bhattacharyya, P. Dey, A. Kundu and A. Raychaudhuri, *Probing universal extra dimension at the International Linear Collider*, Phys. Lett. B 628 (2005) 141 [arXiv:hep-ph/0502031];

A. Datta and S. K. Rai, *Identifying the contributions of universal extra dimensions in the Higgs sector at linear e+ e- colliders*, Int. J. Mod. Phys. A 23 (2008) 519 [arXiv:hep-ph/0509277].
[39] B. Bhattacharjee and A. Kundu, The International Linear Collider as a Kaluza-Klein factory, Phys. Lett. B 627 (2005) 137 [arXiv:hep-ph/0508170].

[40] B. Bhattacharjee, A. Kundu, S. K. Rai and S. Raychaudhuri, Universal Extra Dimensions, Radiative Returns and the Inverse Problem at a Linear e+e- Collider, Phys. Rev. D 78 (2008) 115005 [arXiv:0805.3619 [hep-ph]].

[41] K. Ghosh and K. Huitu, Constraints on Universal Extra Dimension models with gravity mediated decays from ATLAS diphoton search, JHEP 1206 (2012) 042 [arXiv:1203.1551 [hep-ph]].

[42] H. Murayama, M. M. Nojiri and K. Tobioka, Improved discovery of a nearly degenerate model: MUED using MT2 at the LHC, Phys. Rev. D 84, 094015 (2011) [arXiv:1107.3369 [hep-ph]].

[43] C.-R. Chen, M. M. Nojiri, S. C. Park, J. Shu and M. Takeuchi, Dark matter and collider phenomenology of split-UED, JHEP 0909 (2009) 078 [arXiv:0903.1971 [hep-ph]].

[44] K. Kong, S. C. Park and T. G. Rizzo, A vector-like fourth generation with a discrete symmetry from Split-UED, JHEP 1007, 059 (2010) [arXiv:1004.4635 [hep-ph]].

[45] C. Csaki, J. Heinonen, J. Hubisz, S. C. Park and J. Shu, 5D UED: Flat and Flavorless, JHEP 1101, 089 (2011) [arXiv:1007.0025 [hep-ph]].

[46] G.-Y. Huang, K. Kong and S. C. Park, Bounds on the Fermion-Bulk Masses in Models with Universal Extra Dimensions, JHEP 1206, 099 (2012) [arXiv:1204.0522 [hep-ph]].

[47] A. Meade et al. [ATLAS Collaboration], A Measurement of the Ratio of the W + 1 Jet to Z + 1 Jet Cross Sections with ATLAS, arXiv:1110.0435 [hep-ex].

[48] M. Nespolo [CMS Collaboration], W/Z + jets with the CMS detector, J. Phys. Conf. Ser. 323 (2011) 012013.

[49] K. Kong, S. C. Park and T. G. Rizzo, Collider Phenomenology with Split-UED, JHEP 1004 (2010) 081 [arXiv:1002.0602 [hep-ph]].

[50] J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012)

[51] H. C. Cheng, K. T. Matchev and M. Schmaltz, Radiative corrections to Kaluza-Klein masses, Phys. Rev. D 66 (2002) 036005 [arXiv:hep-ph/0204342].

[52] H. C. Cheng, K. T. Matchev and M. Schmaltz, Bosonic supersymmetry? Getting fooled at the LHC, Phys. Rev. D 66 (2002) 056006 [arXiv:hep-ph/0205314].

[53] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. M. Nadolsky and W. K. Tung, New generation of parton distributions with uncertainties from global QCD analysis, JHEP 0207 (2002) 012 [arXiv:hep-ph/0201195].

[54] F. Maltoni and T. Stelzer, MadEvent: Automatic event generation with MadGraph, JHEP 0302 (2003) 027 [arXiv:hep-ph/0208156].