Probing two universal extra dimensions at international linear collider

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We discuss collider signatures of (1, 1)th Kaluza–Klein (KK) mode vector bosons in the framework of two universal extra dimension model, at a future e^+e^- collider. Production of B_μ^{(1,1)} and W_3^{(1,1)}, the (1, 1)th KK mode vector bosons, are considered in association with a hard photon. Without caring about the decay products of B_μ^{(1,1)} or W_3^{(1,1)}, one can measure the masses of these particles just by looking at the photon energy distribution. Once produced B_μ^{(1,1)} (W_3^{(1,1)}) dominantly decays to a pair of jets or to a pair of top quarks. Thus we look for a pair of jets or a pair of top quarks in association with a photon. Upto the kinematic limit (with e^+e^- center-of-mass energies of 0.5 TeV and 1 TeV) of the collider, signals from the B_μ^{(1,1)} production and decay in both the above mentioned channels are greater than the 5σ fluctuation of the Standard Model background with 500 fb^{-1} integrated luminosity. However, the number of events from W_3^{(1,1)} production and decay is smaller and its detection prospect is not very good.

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1. Introduction

Recently lots of attention have been paid to the models of fundamental interactions with one or more extra space like dimensions [1,2]. There is a class of such interesting models where all the Standard Model (SM) fields can access these extra space-like dimensions along with the (3+1)-dimensional Minkowski spacetime. These are collectively called the Universal Extra Dimensional (UED) models [3].

A particular variant of the UED model where all the SM fields propagate in (5+1)-dimensional space–time, namely the two Universal Extra Dimension (2UED) Model has some attractive features. 2UED model can naturally explain the long life time for proton decay [4] and more interestingly it predicts that the number of fermion generations should be an integral multiple of three [5].

As the name suggests, in 2UED, all the SM fields can propagate universally in the six-dimensional (6D) space–time. Four-dimensional (4D) space–time coordinates x^μ (μ = 0, 1, 2, 3) form the usual Minkowski space. Two extra spacial dimensions with coordinates x^4 and x^5 are flat and are compactified with 0 ≤ x^4, x^5 ≤ L. Toroidal compactification of the extra dimensions, leads to 4D fermions that are vector-like with respect to any gauge symmetry. Alternatively, one needs to identify two pairs of adjacent sides of the square. This compactification mechanism automatically leaves at most a single 4D fermion of definite chirality as the zero mode of any chiral 6D fermion [6].

The requirements of anomaly cancellation and fermion mass generation force the weak-doublet fermions to have opposite 6D chiralities with respect to the weak-singlet fermions. So the quarks of one generation are given by Q_± = (U_±, D_±), U_±, D_±... The 6D doublet quarks and leptons decompose into Kaluza–Klein (KK) towers of heavy vector-like 4D fermion doublets with left-handed zero mode doublets. Similarly each 6D singlet quark and lepton decompose into the KK-towers of heavy 4D vector-like singlet fermions along with zero mode right-handed singlets. These zero mode fields are identified with the SM fermions. In 6D, each of the gauge fields, has six components. Upon compactification, they give rise to towers of physical 4D massive spin-1 fields and a tower of spinless adjoints. In a previous work [7] we have discussed the phenomenology of these spinless adjoints in some details. In this Letter, we will be interested in a particular member of the KK-towers of hypercharge gauge boson B_μ and SU(2) gauge boson W_3^μ.

We would like to investigate the production of B_μ and W_3^μ in association with a hard photon at a future e^+e^- linear collider. Somewhat similar things have been discussed in Ref. [8]. Authors in Ref. [8], have considered the production of B_μ is association with a photon. However, they demand that the photon is undetectable and is lost along the beam pipe. This implies that the identification and mass determination of B_μ, crucially depend on jet (coming from the decay of B_μ) reconstruction and jet energy measurement. In contrast, we look for a final state consisting of a hard photon and the decay products (which may or may not be...
detectable always) of $B_{\mu}$ and $W^{3}_{\mu}$. In some sense our method is complementary to that used in Ref. [8]. The advantages of tagging the photon, will be illuminated in the next section.

The tree-level masses for $(j, k)$th 1 KK-mode particles are given by $\sqrt{M_{j,k}^{2} + m_{0}^{2}}$, where $M_{j,k} = \sqrt{j^{2} + k^{2}}/R$. The radius of compactification, $R$, is related to the size of the extra dimensions, $L$ via the relation $L = \pi R$. $m_{0}$ is the mass of the corresponding zero mode particle. As a result, the tree-level masses are approximately degenerate. This degeneracy is lifted by radiative corrections.

Conservation of momentum (along the extra dimensions) in the full theory, implies KK number conservation in the effective 4D theory. SM-like interactions in the 6D (called the bulk interactions), give rise to the KK-number conserving as well as KK-parity conserving interactions, in 4D effective theory after compactification. However, one can generate KK number violating (KK parity conserving) operators at one loop level, starting from the bulk interactions. Structure of the theory demands that these operators can only be on (0, 0), (0, L) and (L, L) points of the chiral square. In this Letter, we will exploit one such KK-number violating coupling to find a characteristic signature of 2UED model at an $e^{+}e^{-}$ collider. Namely, we will discuss the collider signatures of $B^{(1,1)}_{\mu}$ and $W^{(1,1)}_{3\mu}$, the (1, 1)th KK excitations of the U(1) and neutral SU(2) gauge bosons. $B^{(1,1)}_{\mu}$ ($W^{(1,1)}_{3\mu}$) couples to an electron–positron pair via KK-number violating coupling [9]:

$$\mathcal{L} = \left[ c_{L}^{e} p_{L} + c_{R}^{e} p_{R} \right] \gamma \mu e V_{\mu}^{(1,1)}.$$  \hspace{1cm} (1)

Where,

$$c_{L}^{e} = \frac{g^{2}}{16\pi^{2}} \left( \frac{9}{8} + \frac{91g^{2}}{24g^{2}} \right) \ln \frac{M_{j,k}^{2}}{m_{0}^{2}},$$

$$c_{R}^{e} = \frac{g^{2}}{16\pi^{2}} \left( \frac{59}{6} \right) \ln \frac{M_{j,k}^{2}}{m_{0}^{2}},$$

$$c_{L}^{W} = \frac{g^{2}}{16\pi^{2}} \left( \frac{-11}{24} + \frac{3g^{2}}{8g^{2}} \right) \ln \frac{M_{j,k}^{2}}{m_{0}^{2}},$$

$$c_{R}^{W} = 0.$$  \hspace{1cm} (2)

These couplings also have logarithmic dependence on the cutoff scale, $M_{c}$, of the theory. We assume $M_{c}$ to be 10 times the compactification scale $R^{-1}$ following [9].

Contributions to the KK-number violating operators like Eq. (1) might be induced by physics above the cut-off scale. We assume that those UV generated localized operators are also symmetric under KK parity, so that the stability of the lightest KK particle which can be a promising dark matter candidate [11], is ensured. Loop contributions by the physics below cut-off scale $M_{s}$ are used to renormalize the localized operators [12].

2. Signatures at future $e^{+}e^{-}$ collider with photon tag

Resonance production of $B^{(1,1)}_{\mu}$, has been investigated in the context of Tevatron and LHC in [9,10] and in the context of future $e^{+}e^{-}$ collider in [8]. However, in this Letter, we will reconsider the prospects of $B^{(1,1)}_{\mu}$ (also $W^{(1,1)}_{3\mu}$) production and detection at future $e^{+}e^{-}$ colliders, exploiting the KK-number violating couplings defined in Eq. (1).

There is a disadvantage of $e^{+}e^{-}$ collision. Unless the mass of the particle, we want to produce, matches exactly with the $e^{+}e^{-}$ center-of-mass energy, resonance production cross-section is miniscule. This compels us to consider the $B^{(1,1)}_{\mu}$ ($W^{(1,1)}_{3\mu}$) production in association with a photon ($e^{+}e^{-} \rightarrow \gamma B^{(1,1)}_{\mu}$, $\gamma W^{(1,1)}_{3\mu}$). This particular production mechanism has many interesting consequences. First of all, just measuring the photon energy one can have the knowledge of the mass of $B^{(1,1)}_{\mu}$, without caring about the decay products of $B^{(1,1)}_{\mu}$. Moreover, we will also notice that, the production cross-section grows with mass of $B^{(1,1)}_{\mu}$ ($W^{(1,1)}_{3\mu}$).

$B^{(1,1)}_{\mu}$ and $W^{(1,1)}_{3\mu}$ production in association with a photon takes place in $e^{+}e^{-}$ collision, via $t(u)$ channel. Spin averaged matrix element squared at the LO is given by:

$$\sum |\mathcal{M}|^{2} = 4\pi\alpha_{em}(c_{L}^{V} + c_{R}^{V})^{2} \left( \frac{u}{t} + \frac{t}{u} + \frac{2m^{2}_{0}s}{ut} \right),$$  \hspace{1cm} (3)

$s, t, u$ are the usual Mandelstam variables, and $c_{L}^{V}, c_{R}^{V}$ are defined in Eq. (2). The numerical values of the cross-sections are presented in Fig. 1 against the masses of $B^{(1,1)}_{\mu}$ and $W^{(1,1)}_{3\mu}$ for two different values of $e^{+}e^{-}$ center-of-mass energies. Fig. 1 shows a very interesting variation of cross-section. In spite of the fact that, the couplings in Eq. (1) do not increase with the masses or $R^{-1}$, the cross-section increases when the mass of $V^{(1,1)}_{\mu}$ approaches closer to the center-of-mass energy, which is fixed for a particular collider. This, in fact, is a more general phenomenon not specific to the 2UED model. The probability of the photon emission from one of the initial $e^{-}$ or $e^{+}$, increases with the diminishing photon energy. One can easily check that for a fixed center-of-mass energy ($\sqrt{s}$)
of the collider, photon energy $E_{\gamma}$ is given by: $rac{s-m^2}{2s}$. Thus a KK gauge boson mass closer to the center-of-mass energy reduces the photon energy which in turn increases the cross-section. Similar effects can take place in the cases of single production of sneutrinos [13] (in association with a photon) via lepton number violating couplings; graviton production in ADD or RS model (in association with a photon) [14].

The increase of cross-section with mass can also be very easily understood by looking at Eq. (3). Both, $u$ and $t$ are proportional to the photon energy $E_{\gamma}$. An increasing $B^{(1,1)}_\mu$ or $W^{(1,1)}_{3\mu}$ mass would mean (for a fixed $e^+e^-$ center-of-mass energy) a diminishing $u$ and $t$. This in turn enhances the cross-section with mass.

Rate of $B^{(1,1)}_\mu$ production is always an order of magnitude higher than the rate of $W^{(1,1)}_{3\mu}$ production over the mass range upto the kinematic limit. $W^{(1,1)}_{3\mu}$ couples only to the left-handed electrons via the SU(2) gauge coupling. On the other hand, $B^{(1,1)}_\mu$ couples to both left- and the right-handed electrons (see Eq. (2)). Moreover, a partial cancellation between two terms in the expression of $\epsilon^{3\mu}$ makes the $W^{(1,1)}_{3\mu}$ production cross-section smaller.

The dominance of $B^{(1,1)}_\mu$ cross-section over the $W^{(1,1)}_{3\mu}$ can be partially explained from these couplings.

We can now discuss the signals of $B^{(1,1)}_\mu$ and $W^{(1,1)}_{3\mu}$ production at $e^+e^-$ collisions. Once produced, $B^{(1,1)}_\mu$ ($W^{(1,1)}_{3\mu}$) dominantly decays to a pair of light quark jets. It also decays to a $b\bar{b}$ or $t\bar{t}$ pair. We collectively look for two jets (light or $b$-flavoured) from the decay of $B^{(1,1)}_\mu$ or $W^{(1,1)}_{3\mu}$ and a nearly mono-energetic photon. If we look at the energy distribution of the photons, $B^{(1,1)}_\mu$ and $W^{(1,1)}_{3\mu}$ production would be characterised by two (mono-energetic) peaks separated by, $\Delta E_{\gamma} = \frac{m^2_{B^{(1,1)}_\mu} - m^2_{W^{(1,1)}_{3\mu}}}{s}$. Production of $B^{(1,1)}_\mu$ ($W^{(1,1)}_{3\mu}$) in association with a photon, is twofold advantageous. Instead of a fixed center-of-mass energy, now the effective center-of-mass energy of the collision (which produces the new physics) can vary over a range thus makes it possible to produce $B^{(1,1)}_\mu$ and/or $W^{(1,1)}_{3\mu}$ with different masses. Moreover, by measuring the energy of the photon, we can determine the masses of $B^{(1,1)}_\mu$ and $W^{(1,1)}_{3\mu}$ without caring about the decays of these particles. $B^{(1,1)}_\mu$ or $W^{(1,1)}_{3\mu}$ dominantly decays to a pair of jets. One can thus measure the masses of $B^{(1,1)}_\mu$ or $W^{(1,1)}_{3\mu}$ directly by measuring the jet energies. Authors in Ref. [8], have investigated the production of $B^{(1,1)}_\mu$ in $e^+e^-$ collision. They have emphasised on directly measuring the jet energies and reconstructing the $B^{(1,1)}_\mu$ mass. This involves, identification and energy measurement of both the jets coming from the $B^{(1,1)}_\mu$ decay. However, photon identification and measurement of its energy in electromagnetic calorimeter can be done more easily in comparison to the same exercise with the jets.

For an ideal detector with infinitely high resolution, the photon energy distribution is ideally a delta-function at $E_{\gamma} = \frac{s-m^2_{B^{(1,1)}_\mu}}{2s}$. As a consequence of finite detector resolution and initial state radiation (ISR) the photon energy distribution is smeared. However, the effects which smear the $E_{\gamma}$ peak, cannot change the position of the peak, enabling us to measure the masses of $B^{(1,1)}_\mu$ or $W^{(1,1)}_{3\mu}$ just by looking at the position of the peaks in the $E_{\gamma}$ distribution. This method works well, independent of any particular decay mode of $B^{(1,1)}_\mu$ or $W^{(1,1)}_{3\mu}$. This in turn enhances the cross-section with mass.

For the production of $B^{(1,1)}_\mu$, we define three bins in $E_{\gamma}$ distribution with different masses.

The total number of signal events in the bins corresponding to the peak in the photon energy distributions and its two adjacent bins are also presented in Table 1.

The $E_{\gamma}$ distribution for $\gamma +2j$-events for signal (dashed histogram) and background (solid histogram) for an $e^+e^-$ center-of-mass energy of 1 TeV is shown in Fig. 2. We have used $R^{-1} = 630$ GeV, and $\sqrt{s} = 1$ TeV. The monoenergetic (in the case of signal) photon peak is smeared due to ISR effects and finite detector resolution. We have used $R^{-1} = 630$ GeV, and $\sqrt{s} = 1$ TeV.
Table 1
Number of $\gamma + 2\ell$ signal and SM background events for two values of $e^+e^-$ center-of-mass energies assuming 500 fb$^{-1}$ integrated luminosity. $1\sigma$ fluctuations of the background events are also shown in the brackets. The entries marked with a dash correspond to the situations when number of events is too small, or $B^{(1,1)}_\mu$ ($W^{(1,1)}_{3\mu}$) production is kinematically disallowed.

| $e^+e^-$ C-o-M Energy | $R^{-1}$ in GeV | $B^{(1,1)}_\mu$ | $m^{(1,1)}_\mu$ GeV | $B^{(3,1)}_\mu$ | $m^{(3,1)}_\mu$ GeV | Background Event |
|----------------------|-----------------|----------------|------------------|----------------|----------------|----------------|
| 500 GeV              |                 |                |                  |                |                  |                |
| 280                  | 387.3           | 5900           | 19258 (139)      | 433.8          | 253            | 26593 (163)   |
| 290                  | 401.1           | 6713           | 20368 (143)      | 448.7          | 349            | 34031 (184)   |
| 300                  | 414.9           | 7701           | 22207 (149)      | 463.7          | 520            | 50011 (224)   |
| 310                  | 428.8           | 9005           | 24814 (158)      | 478.7          |                |                |
| 340                  | 470.3           | 24296          | 59938 (245)      | 523.6          |                |                |
| 300                  | 414.9           | 348            | 2889 (54)        | 463.7          | 10             | 2499 (50)     |
| 400                  | 553.3           | 430            | 2038 (45)        | 613.8          | 14             | 1932 (44)     |
| 550                  | 760.8           | 948            | 2096 (46)        | 840.4          | 43             | 2538 (50)     |
| 630                  | 871.4           | 2082           | 3013 (55)        | 961.5          | 210            | 8444 (92)     |
| 690                  | 954.4           | 6552           | 7482 (87)        | 1052.4         |                |                |

| 1 TeV                |                 |                |                  |                |                  |                |
| 250                  | 345.8           |                |                  | 389.1          | 8              | 484 (22)       |
| 280                  | 387.3           | 519            | 484 (22)         | 433.8          | 18             | 774 (28)       |
| 295                  | 408.1           | 776            | 506 (23)         | 456.2          | 30             | 1305 (36)      |
| 310                  | 428.8           | 1115           | 711 (27)         | 478.7          | 46             | 1673 (41)      |
| 340                  | 470.3           | 3586           | 2248 (48)        | 523.6          |                |                |
| 300                  | 414.9           | 40             | 63 (8)           | 463.7          |                |                |
| 400                  | 553.3           | 76             | 77 (9)           | 613.8          |                |                |
| 550                  | 760.8           | 189            | 126 (11)         | 840.4          | 5              | 178 (13)       |
| 630                  | 871.4           | 461            | 245 (16)         | 961.5          | 25             | 747 (27)       |
| 690                  | 954.4           | 1482           | 654 (26)         | 1052.5         |                |                |

Table 2
Number of $\gamma + 2\ell$ signal and SM background events for two values of $e^+e^-$ center-of-mass energies assuming 500 fb$^{-1}$ integrated luminosity. $1\sigma$ fluctuations of the background events are also shown in the brackets. The entries marked with a dash correspond to the situations when number of events are too small, or $B^{(3,1)}_\mu$ ($W^{(1,1)}_{3\mu}$) decay to $t\bar{t}$ is kinematically not possible.

| $e^+e^-$ C-o-M Energy | $R^{-1}$ in GeV | $B^{(1,1)}_\mu$ | $m^{(1,1)}_\mu$ GeV | $B^{(3,1)}_\mu$ | $m^{(3,1)}_\mu$ GeV | Background Event |
|----------------------|-----------------|----------------|------------------|----------------|----------------|----------------|
| 500 GeV              |                 |                |                  |                |                  |                |
| 250                  | 345.8           |                |                  | 389.1          | 8              | 484 (22)       |
| 280                  | 387.3           | 519            | 484 (22)         | 433.8          | 18             | 774 (28)       |
| 295                  | 408.1           | 776            | 506 (23)         | 456.2          | 30             | 1305 (36)      |
| 310                  | 428.8           | 1115           | 711 (27)         | 478.7          | 46             | 1673 (41)      |
| 340                  | 470.3           | 3586           | 2248 (48)        | 523.6          |                |                |
| 300                  | 414.9           | 40             | 63 (8)           | 463.7          |                |                |
| 400                  | 553.3           | 76             | 77 (9)           | 613.8          |                |                |
| 550                  | 760.8           | 189            | 126 (11)         | 840.4          | 5              | 178 (13)       |
| 630                  | 871.4           | 461            | 245 (16)         | 961.5          | 25             | 747 (27)       |
| 690                  | 954.4           | 1482           | 654 (26)         | 1052.5         |                |                |

3. Conclusion
To summarise, we have discussed a possible signature of $B^{(1,1)}_\mu$ and $W^{(3,1)}_{3\mu}$ production along with a hard photon, in the framework of 2UED model, at a future $e^+e^-$ collider. Once produced these gauge bosons decay either to a pair of light quarks or to a pair of top quarks. So the signatures of these vector bosons are a pair of jets or a pair of top quarks with a nearly monoenergetic photon. Production of these (1, 1)-mode gauge bosons along with a single hard photon is advantageous. Without caring about the decay products of $B^{(1,1)}_\mu$ and $W^{(3,1)}_{3\mu}$, one can measure the masses of these particles by measuring the energy of the photon. Number of signal events from $B^{(1,1)}_\mu$ production is always greater than the $5\sigma$ fluctuation of the SM background, for $R^{-1}$ values up to the kinematic limit of the collision. Rate of $W^{(3,1)}_{3\mu}$ production is small and cannot stand over the SM background in either 2$\ell$ or 2$\ell$ channel. Thus the measurement of the possible correlation between the masses of $B^{(1,1)}_\mu$ and $W^{(3,1)}_{3\mu}$ and their signal strengths is not pos-
sible. However, the number of events from $B_{μ}^{(1,1)}$ production and decay (both in $γ + 2j$ and $γ + 2t$ channels) are large. These enable one to measure the cross-sections in these channels precisely. The relative strength of the $γ + 2j$ and $γ + 2t$ signals thus can be measured. This ratio of the cross-sections are equal to the ratio of $B_{μ}^{(1,1)}$ decay widths into $jj$ and $tt$ channels. Interestingly this ratio is independent of the cut-off scale of the theory. Thus experimentally measured ratio can be contrasted with the theoretical predictions from 2UED model.

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