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Diphoton signal via Chern-Simons interaction in a warped geometry scenario

Nabarun Chakrabarty[*] and Biswarup Mukhopadhyaya[†]
Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad 211019, India

Soumitra SenGupta[‡]
Department of Theoretical Physics, Indian Association for the Cultivation of Science, 2A and 2B Raja S.C. Mullick Road, Kolkata 700032, India
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The Kalb-Ramond field, identifiable with bulk torsion in a five-dimensional Randall Sundrum (RS) scenario, has Chern-Simons interactions with gauge bosons, from the requirement of gauge anomaly cancellation. Its lowest Kaluza Klein (KK) mode on the visible 3-brane can be identified with a spin-0 *CP*-odd field, namely, the axion. By virtue of the warped geometry and Chern-Simons couplings, this axion has unsuppressed interactions with gauge bosons in contrast to ultra-suppressed interactions with fermions. The ensuing dynamics can lead to a peak in the diphoton spectrum, which could be observed at the LHC, subject to the prominence of the signal. Moreover, the results can be numerically justified when the warp factor is precisely in the range required for stabilization of the electroweak scale.

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I. INTRODUCTION

Suppose there is fundamental spin-0 particle in nature, whose couplings to all Standard Model (SM) particles are extremely suppressed, the only exception being pairs of gauge bosons. In such a case, such interactions should constitute the sum and substance of its phenomenology observable at the Large Hadron Collider (LHC), provided that it is within the kinematic reach of the latter.

Such a situation is not altogether far-fetched. A case in point is a *CP*-odd spin-0 axion field, in terms of which a Kalb-Ramond (KR) antisymmetric tensor field strength can be defined. As we emphasize further in the remaining part of this paper, the KR field exhibits some very interesting properties if it propagates in bulk in a $(1+4)$ dimensional warped geometry scenario as proposed first by Randall and Sundrum. However, the theory is not in general anomaly-free if it arises from a still higher-dimensional scenario such as 10-dimensional supergravity. This problem is avoided (see Sec. II) if the KR field is endowed with Chern-Simons (CS) terms couplings with gauge bosons, also propagating in the bulk [1]. On compactification of the warped extra dimension, the CS term has unsuppressed interaction strengths of its zero mode with gauge boson pairs on the $(1+3)$ dimensional visible brane. This unsuppressed character is in turn translated into the interaction of the axion field, in terms of which the zero-mode KR field strength is expressed. On the other hand, the fermionic couplings of the CS-axion turn out to be suppressed as an artifact of the given scenario. With a nonperturbatively acquired mass of this axion, it can have interesting LHC phenomenology where the CS-driven gluon fusion process can produce it, followed by its decays into gauge boson pairs, of which the most spectacular signal consists in diphoton invariant mass peaks. The expected rates of such peaks are estimated in this paper. We mention in this connection that a recent surge of interest on such diphoton peaks came with the apparent occurrence of a diphoton peak at about 750 GeV in the initial 13 TeV run of the LHC. It was first reported in the preliminary announcement of the 13 TeV run [2,3] and corroborated in the recent reports in the recent Moriond meeting [4]. It led to an avalanche of explanations offered in context of various new physics scenarios (see for a representative list [5–39]). Even though the signal ultimately failed to persist, it could nonetheless glorify the importance of the diphoton final state in detecting a spin-0 TeV-scale resonance, that could indeed be a reality for higher axion masses.

As has been stated already, we present our study in the context of a five-dimensional Randall-Sundrum scenario with bulk space-time torsion identifiable with a Kalb-Ramond tensor field. The massless four-dimensional projection of this field is expressible in terms of an axion which may acquire a mass term nonperturbatively. While this axion field has extremely suppressed coupling with fermions on the four-dimensional visible brane, it can have enhanced interaction with gauge boson pairs via Chern-Simons(CS) terms. Using such CS terms as the driving dynamics, we examine the diphoton production rates in this study. To make matters more practical from the experimental perspective,

[*]nabarunc@hri.res.in
[†]biswarup@hri.res.in
[‡]tpssg@iacs.res.in

we choose only those values of the warp factor in the five-dimensional geometry, which not only can explain the hierarchy between the Planck and electroweak scales, but also generate KK gauge boson masses above the lower bound set by LHC. We present our results for different axion masses.

This paper is planned as follows. In Sec. II, we introduce the theoretical framework. Prospects of embedding the recently observed resonance in that framework are studied in Sec. III. A more general discussion on other possible diphoton resonances can be found in Sec. III. We summarize in Sec. IV.

II. THE SCENARIO

As stated at the beginning, we consider a five-dimensional Randall-Sundrum (RS) scenario, where the extra dimension is a $\mathcal{Z}_2$ orbifold of radius r_c. There are two branes at the orbifold fixed points, i.e., $\phi = 0$ and $\phi = \pi$, where ϕ is the angular variable for the compact coordinate. The five-dimensional metric is

$$ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2, \tag{2.1}$$

with $\eta_{\mu\nu} = \{-,+,+,+\}$ the Minkowski metric and k (related to the bulk cosmological constant) the order of the four-dimensional Planck mass M_P.

The five-dimensional Planck mass M is related to M_P as

$$M_P^2 = \frac{M^3}{k}(1 - e^{-2kr_c\pi}). \tag{2.2}$$

Resolution of the naturalness problem requires $kr_c \simeq 11.5$. Attempts towards finding a warped-geometric explanation to the 750 GeV resonance can be seen in [40–53].

The presence of CS terms can be motivated if the aforesaid scenario is the descendant of, say, a ten-dimensional supergravity theory. There the KR field strength tensor is augmented by a set of CS terms in order to cancel gauge anomalies.[1] This anomaly cancellation feature is protected in four-dimensional effective theory with a modification of the gauge-KR coupling by an appropriate volume modulus factor.

When the five-dimensional space-time has torsion along with curvature, the torsion field can be identified with the KR field [54–63]. It has been shown earlier that such a field is suppressed in $(1+3)$ dimensions due to the RS geometry, thus explaining why our observed Universe is controlled primarily by curvature rather than torsion.

The five-dimensional Einstein-Maxwell-Kalb-Ramond (EKMR) action in the Einstein frame reads

$$S_{\rm eff} = \int d^5x\sqrt{-G}\left[R - \frac{1}{4}F_{MN}F^{MN} - \frac{1}{12}\bar{H}_{MNL}\bar{H}^{MNL}\right] \tag{2.3}$$

$$\bar{H}_{MNL} = H_{MNL} + \frac{2}{M^{3/2}}B_{[M}F_{NL]} + \frac{2}{M^{3/2}}W^i_{[M}W^i_{NL]} + \frac{2}{M^{3/2}}G^b_{[M}G^b_{NL]}, \tag{2.4}$$

where a sum over $i = 1, 2, 3$ and $b = 1, 2.., 8$ is implied. In addition we have

$$H_{MNL} = \partial_{[M}B_{NL]}. \tag{2.5}$$

Here, B_{NL} refers to the Kalb-Ramond (KR) two form in five dimensions. Besides, $B_M(x,\phi)$, $W^i_M(x,\phi)$ and $G^b_M(x,\phi)$, respectively, refer to the $U(1)_Y$, $SU(2)_L$ and $SU(3)_c$ gauge fields in the bulk with F_{NL}, W^i_{NL} and G^b_{NL} as the corresponding field strengths.[2] The gauge $SU(2)_L$ and $SU(3)_c$ gauge indices read i and b respectively. Further, KR gauge invariance allows us to do gauge fixing using $B_{\mu y} = 0$.

With the SM gauge fields in the bulk, the Kaluza-Klein towers for them as well as the KR field on the visible brane are given by

$$B_{\mu\nu}(x,\phi) = \sum_{n=1}^{\infty} B^n_{\mu\nu}(x)\frac{\chi^n(\phi)}{\sqrt{r_c}} \tag{2.6}$$

$$C_\mu(x,\phi) = \sum_{n=1}^{\infty} C^n_\mu(x)\frac{\psi^n(\phi)}{\sqrt{r_c}}, \tag{2.7}$$

where C stands for the towers corresponding to the SM gauge fields, viz., B, W and G. The zero-mode for the KR field obeys the following equation:

$$\frac{1}{r_c^2}\frac{d^2\chi^0}{d\phi^2} = 0. \tag{2.8}$$

The solution reads

[1]The massless sector of D = 10 supergravity multiplet contains a second rank antisymmetric tensor field $B_{\mu\nu}$ with a corresponding third rank field strength $H_{\mu\nu\alpha}$. This field strength can also be interpreted as the background space-time torsion. The field $B_{\mu\nu}$ plays a crucial role in canceling the gauge anomaly originating from the one loop hexagon diagrams with six external legs of gauge fields with chiral fermions in the loop. If the third rank field strength is now modified with an appropriate Chern-Simons term as $H_{\mu\nu\alpha} = \partial_{[\mu}B_{\nu\alpha]} + \frac{A_{[\mu}F_{\nu\alpha]}}{M_P}$, then the corresponding tree diagram that is generated with the Kalb-Ramond field as propagator between the gauge fields at the two vertices exactly cancels the hexagon gauge anomaly [1].

[2]The CS coupling in five dimensions will always carry a $\frac{1}{M^{3/2}}$ on dimensional grounds. However, the numerical factors may not be strictly the same for all gauge fields. For simplicity, we assume universal couplings in this work.

$$\chi^0(\phi) = c_1 + c_2|\phi|. \tag{2.9}$$

Continuity of the first derivative of $\chi^0(\phi)$ at the orbifold fixed points $\phi = 0, \pm\pi$ gives $c_2 = 0$. Here, c_1 is fixed using the orthonormality condition

$$\int e^{2kr_c\phi}\chi^m(\phi)\chi^n(\phi)d\phi = \delta_{mn}. \tag{2.10}$$

This leads to the following zero-mode profiles:

$$\chi^0(\phi) = \sqrt{2kr_c}e^{-kr_c\pi} \tag{2.11}$$

$$\psi^0(\phi) = \frac{1}{\sqrt{2\pi}}. \tag{2.12}$$

Here, $H^0_{\mu\nu\lambda}$, the field strength of $B^0_{\mu\nu}$ $H^0_{\mu\nu\lambda}$, can be expressed as

$$H^0_{\mu\nu\lambda} = \epsilon_{\mu\nu\lambda\rho}\partial^\rho a.$$

Here, a denotes a CP-odd scalar, called the KR axion. Such an axion acquires a mass term through nonperturbative effects confined to the TeV brane such as instanton corrections [64]. This mass is *prima facie* a free parameter, which can be around a TeV scale.[3] The kinetic terms of a and its coupling to the SM gauge fields via the Chern-Simons terms take the form [58]

$$S_{\rm Kin} = -\frac{1}{2}\eta^{\mu\nu}\partial_\mu a\partial_\nu a \tag{2.13}$$

$$S_{\rm CS} = f[aB_{\mu\nu}\tilde{B}^{\mu\nu} + aW^i_{\mu\nu}\tilde{W}^{i\mu\nu} + aG^b_{\mu\nu}\tilde{G}^{b\mu\nu}], \tag{2.14}$$

where $f = -\frac{e^{kr_c\pi}}{\sqrt{2\pi}kr_cM_P}$ quantifies the coupling of the axion to the SM gauge bosons. Moreover, $\tilde{B}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\lambda\rho}B_{\lambda\rho}$ etc. denote the dual of the original field strength.

It should be noted that the CS terms enable the axion to have enhanced coupling to gauge field pairs, by virtue of the specific nature of the warped geometry. In contrast, it has been found [63,65] that a has interaction to fermion pairs of the form$\sim\frac{e^{-kr_c\pi}}{M_P}$. As a result, both its production rate via gluon fusion and its diphoton partial decay width are enhanced to an extent to be decided by the acquired mass of the axion on the TeV brane.

The expressions for the leading order decay widths of a to various VV (pair of gauge bosons) states are

$$\Gamma_{a\to\gamma\gamma} = \frac{1}{4\pi}f^2m_a^3 \tag{2.15}$$

$$\Gamma_{a\to gg} = \frac{2}{\pi}f^2m_a^3 \tag{2.16}$$

$$\Gamma_{a\to WW} = \frac{f^2m_a^3}{2\pi}\left(1-\frac{4m_W^2}{m_a^2}\right)^{3/2} \tag{2.17}$$

$$\Gamma_{a\to ZZ} = \frac{f^2m_a^3}{4\pi}\left(1-\frac{4m_Z^2}{m_a^2}\right)^{3/2}. \tag{2.18}$$

III. ANALYSIS STRATEGY AND NUMERICAL PREDICTION

We have the following expression for a production cross section via gluon fusion

$$\sigma_{pp\to a}(fb) = c_{gg}\frac{\Gamma_{a\to gg}(\text{GeV})}{m_a s}\times 0.3894\times 10^{12}. \tag{3.1}$$

Here, c_{gg} comes from convoluting over the parton densities,

$$c_{gg} = \frac{\pi^2}{8}\int\frac{dx}{x}g(x)g\left(\frac{m_a^2}{xs}\right). \tag{3.2}$$

For practical purposes, we take $c_{gg}\simeq 2137$. The cross section to the diphoton final state is then straightforwardly obtained by multiplying with the corresponding branching ratio,

$$\sigma_{pp\to a\to\gamma\gamma} = \sigma_{pp\to a}\times\frac{\Gamma_{a\to\gamma\gamma}}{\Gamma_a}. \tag{3.3}$$

The couplings of the axion to the gauge boson pairs are taken to be universal in this study. This makes the branching ratio to a given VV state independent of kr_c, for a fixed axion mass.

Both the production cross section of a as well as its partial width to gg state are prone to QCD corrections. To encapsulate its effect, one can, in principle, scale both the production cross section as well the partial width by some $K_{\rm QCD}$. Considering that the dominant contribution to Γ_a comes from the gg state and that $K_{\rm QCD}$ is expected to be greater than unity, its effect in the diphoton cross section largely cancels out.

We mention in this context that we have also implemented the effective Lagrangian into the FeynRules package [66]. Subsequently, the $pp\to a$ cross section and its decay rates to various channels were cross checked using the tool MadGraph5_aMC@NLO [67].

The diphoton rate is very sensitive kr_c, precisely due to its exponential dependence on the latter. So are the masses of the graviton and gauge boson KK excited states. Different values for the parameter $\frac{k}{M_{\rm Pl}}$, all less than unity,

[3] It should be noted, however, that the possibility of this mass lying within the reach of the LHC is *not predicted* by the scenario considered here. The analysis presented by us is more in a 'looking under the lamppost' spirit, since diphoton signals are in any case of great curiosity and phenomenological significance.

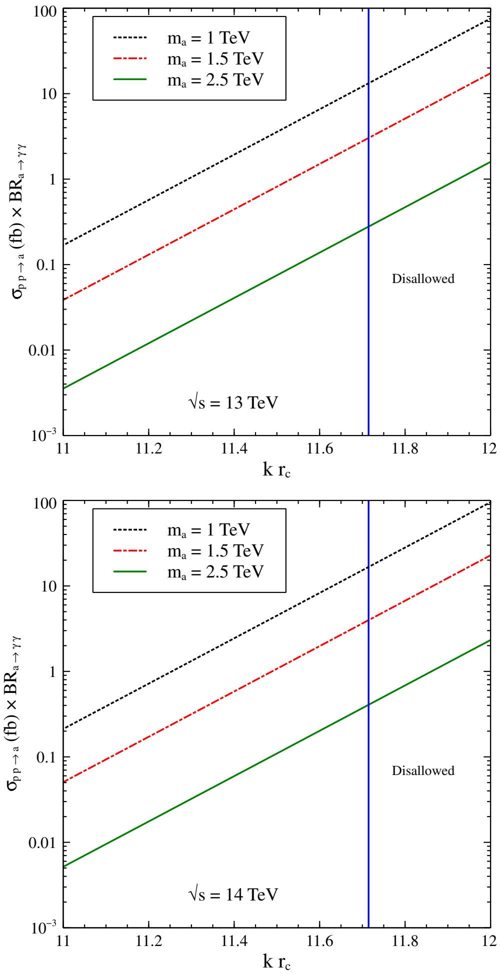

FIG. 1. Diphoton cross sections at LHC-13 and LHC-14 for $m_a = 1$, 1.5 and 2.5 TeV. The region on the right of the vertical line corresponds to a KK gauge boson below the existing bound.

have been chosen while plotting, so that the bulk curvature is less than the Planck scale [68]. Without this constraint, the classical solution of five-dimensional Einstein's equation cannot be trusted.

With $k = 0.7 M_{\mathrm{Pl}}$ and requiring the first gauge boson KK excitation to be heavier than 3.4 TeV [69][4] leads to $kr_c \leq 11.72$. For a given kr_c, this upper bound gets tighter upon using a smaller value for k.

[4]The limit from the nonobservation of dilepton peaks, as obtained in [69], depends on the decay width of the heavier vector boson. The limit is as strong as 4.05 TeV for the spin-1 particle having SM-like couplings to fermions, while it could be 3 TeV or less with narrower widths. Keeping in mind the fact that a first excited spin-1 KK state has weaker coupling than in the SM, we have taken the limit, somewhat conservatively, as 3.4 TeV. Nonetheless, this leads to a stronger upper limit on kr_c than what can be imposed from KK graviton searches, given the lower bound on the mass of the first graviton KK excited stands at 2.68 TeV [70].

The initial results of the 13 TeV collisions have practically ruled out a diphoton resonance of mass less than 750 GeV that has 'reasonable' interaction strength with SM particles. For the spin-zero axion considered here, an exception may occur only if the warp factor kr_c is way below what is required for addressing the hierarchy between the Planck and electroweak scales. However, higher masses are still within reach. We display the diphoton rates for axion masses around 1, 1.5 and 2.5 TeV in Fig. 1. As expected, the rate goes down as the axion gets heavier. It is seen that a 1 TeV axion can have a production cross section of $\simeq 5$ fb at $\sqrt{s} = 13$ TeV, for $kr_c = 11.6$. This goes up to $\simeq 10$ fb for $kr_c = 11.7$. Dynamically enhancing the rate by increasing kr_c to still higher values will invariably come into conflict with the requirement of heavy KK states. Hence, to get an appreciable significance, one must wait until the LHC-13 gathers more data. The sensitivity however is marginally better for $\sqrt{s} = 14$ TeV. For example, a 1 TeV axion can yield a $\simeq 18$ fb cross section for the diphotons in this case. In principle, the other decay modes (such as digluons) can also be observed at the LHC. However, the observability of these are perhaps more challenging than that for the diphotons, since rates of ZZ peaks undergo branching fraction suppression, while dijet peaks from gluon pairs are swamped by the background.

Figure 2 quantitatively depicts the reach of the 13 TeV LHC in detecting a diphoton resonance that has its origin in the framework under study. While a 1 fb diphoton cross section can be predicted even for a 1.9 TeV axion, a more sizeable rate of 10 fb demands a much lighter axion (≤ 1 TeV). The collider must gather appreciable luminosity to discern a feeble resonant diphoton rate (< 1 fb, say)

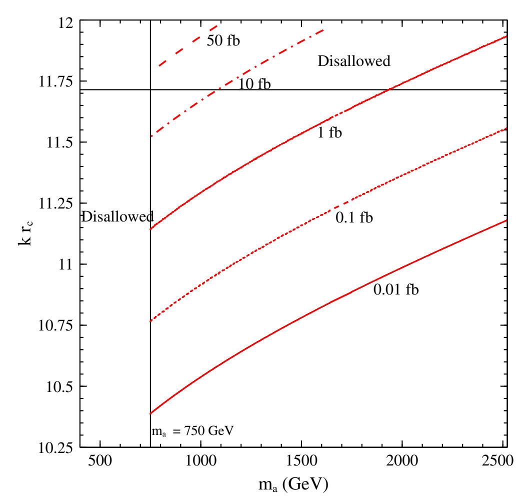

FIG. 2. Contours of constant cross section in the m_a vs kr_c plane. The region to the left of the vertical line is disallowed from the nonobservation of a diphoton resonance below 750 GeV. Similarly, the region above the horizontal line is disallowed from KK gauge boson searches.

from the background. If, upon accumulation of the requisite luminosity, one notices such 'clean' diphoton peaks, the next step would be to see if the WW and ZZ peaks with correlated strengths are also noticeable. In case they are, one has to look further for the presence or absence of corresponding peaks with fermions. If such peaks are absent, then one will be directed to spinless particles which have unsuppressed couplings with gauge boson pairs but no interactions with fermions. One possible interpretation of such coincidence of observed phenomena may be CS dynamics embedded in a warped geometry. The exact estimate of the LHC reach for higher masses will require a careful analysis of cuts and their efficiencies corresponding to the high diphoton invariant mass.

IV. SUMMARY

In conclusion, a bulk KR field in a five-dimensional bulk with RS warped geometry can be connected with an axion in four-dimensions, which, with a nonperturbatively acquired mass, can lead to a bump in the diphoton spectrum. The most notable feature of this framework is that the production as well as decay of the axion is triggered by five-dimensional Chern-Simons terms which are not *ad hoc* introduction but necessitated by the cancellation of gauge anomalies. Even if one makes the simplifying assumption of universal CS couplings for all gauge bosons, the diphoton rate for a 1 TeV axion can attain sizeable values at the 13 TeV LHC. However, a more realistic estimate is only expected to emerge after detector simulation is carried out. We remind that the novelty of the suggested scenario lies in the fact that the very same warp factor, which is responsible for the reported diphoton rate, can bridge the hierarchy between the Planck and electroweak scales. The visibility of a higher diphoton peak can, in principle, improve in the upcoming 14 TeV runs. In all, the final word on a CP-odd scalar around the TeV scale, interacting with the gauge bosons through CS terms, will certainly emerge from accumulating more experimental data. Nonetheless, we find the above correlation rather thought-provoking.

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